In a State of Superposition: Exploring (In)Effective Public Communication About Quantum Technology

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CHAPTER 1

Introduction

In 2012, postdoctoral researcher Krister Shalm at the University of Waterloo's Institute for Quantum Computing gave a TEDx talk in which he said:

> If we were [. . .] to take ourselves and shrink all the way down to the smallest things, like atoms, you'd find that the rules are completely different.
> This is the quantum world, and this is what I study, and in particular what I study is a type of partner dance that happens at the quantum level.
> In my lab, what I do is, I take the smallest chunks of light, we call them photons and I bring them together and I entangle them.
> They become partners, and when I do this, they become connected in a powerful way.
> In fact, it's the strongest connection that physics allows, and what's incredible is they don't have to be next to each other to remain partners, I could take them to opposite ends of the universe and no matter what I did to this one or this one, they would still remain correlated.
> Einstein, he called this spooky action at a distance.
> I prefer to call it partner dancing at a distance.
>
> (TEDx Talks, 2012a)

In this quote, Shalm creatively describes quantum physics, which explains how nature works at the smallest scale. Being a dancer himself, he makes a comparison between partner dancing and a particular phenomenon in quantum physics, called quantum entanglement. The comparison does not only remain in linguistic form - at the end of Shalm's talk, six swing dancers on stage, and almost 500 dancers from 36 cities worldwide on video, illustrate the idea of quantum entanglement through dance. This is an example of a creative way to communicate quantum physics to a broader, non-expert audience.

The type of science communication illustrated above can potentially influence non-experts' attitudes of and engagement with a new technology: quantum technology. Scientists around the world are developing this emergent technology by manipulating quantum phenomena, such as quantum entanglement, to their own design (Dowling & Milburn, 2003). Quantum technology is expected to have a significant impact on society in the future (Stichting Quantumdelta NL, 2020). For example, the technology is expected to enable the simulation of new materials and medicines (Outeiral et al., 2021), to provide fundamentally secure communication, which could enable, for example, secure online voting (Wehner et al., 2018), and to improve the detection of small, underground objects (Crawford et al., 2021). At the same time, the technology could increase the digital divide between rich and poor countries (Ten Holter et al., 2022) and be exploited by criminals, for instance when they acquire unauthorized access to facilities such as energy plants or air traffic control systems (Vermaas et al., 2019).

Non-experts are likely not (yet) familiar with quantum science and technology. Therefore, in communication about quantum science and technology, the way information is formulated can be important. For example, through the sentence 'Einstein, he called this spooky action at a distance', Krister Shalm presents quantum entanglement as something spooky. Such information may make the field of quantum technology seem inaccessible to non-experts and thereby influence their engagement with the field (Coenen et al., 2022; Vermaas, 2017). When non-experts hear that even physicists like Albert Einstein believed quantum entanglement is spooky, they may consequently feel that they themselves cannot understand and engage with information about quantum technology (Coenen et al., 2022; Vermaas, 2017, see).

In addition, the sentence 'I prefer to call it partner dancing at a distance' may also influence non-experts' engagement with quantum technology. By comparing an abstract, counterintuitive phenomenon (quantum entanglement) with a more familiar and concrete image (a partner dance), such information not only explains the science, but could also elicit some sort of emotional response (Grinbaum, 2017). According to Grinbaum (2017), these sorts of comparisons are useful in helping non-expert audiences understand what quantum experts do on a daily basis, and at the same time, help them experience the beauty of quantum physics.

In the scientific literature, several concerns have been raised about the way quantum science and technology are currently communicated to broader, non-expert audiences (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021;

Seskir et al., 2023; Vermaas, 2017). For example, there are concerns about public communication presenting quantum physics as something spooky or enigmatic (Coenen et al., 2022; Vermaas, 2017), and omitting quantum phenomena explanations (Grinbaum, 2017). In addition, possible opportunities for communication about quantum technology are also mentioned (Grinbaum, 2017; Roberson et al., 2021), such as the use of metaphors to explain counterintuitive quantum phenomena (Grinbaum, 2017). However, to date, it is unclear whether these concerns and opportunities will actually result in problems and benefits, because it is not yet clear what public communication about quantum science and technology exactly looks like, nor is it clear what effect certain communicative decisions have on the public.

This dissertation therefore focuses on the following 3 aims:

1. To investigate the occurrence of potential popularisation issues mentioned in the scientific literature around quantum science and technology in public communication.
2. To investigate the effect of these potential issues on public engagement with quantum technology.
3. To what extent metaphors make quantum phenomena more comprehensible, and whether that consequently influences people's attitudes towards quantum technology.

To set the stage of this dissertation, the remainder of this chapter will first introduce the field of quantum science and technology, followed by a discussion of the role that science communication can play in this type of science and technology. The chapter will conclude with an outline of this dissertation.

1.1 The field of quantum science and technology

Quantum physics plays a central role in our daily lives. Our understanding of quantum physics has led to many of the technologies we use today, such as computers, tablets and smartphones (in which the semiconductor chip is an integral part), lasers and MRI scanners (Dowling & Milburn, 2003). These technologies originate from what we call the *first quantum revolution* (Dowling & Milburn, 2003).

To understand the origins of the field, we have to return to the period when quantum physics was formulated. The first quantum revolution began at the start of the 20th century. A key moment early in this revolution was the fifth Solvay International

Conference, entitled 'Electrons and Photons', held in 1927 (Golub & Lamoreaux, 2023). The conference brought together 29 of the most prominent physicists of that time in Brussels, 17 of whom were, or would become, Nobel Prize winners (Wikipedia contributors, 2025b). To this day, it is viewed as one of the most important conferences in the history of physics (Golub & Lamoreaux, 2023). Some physicists at the conference raised objections to quantum theory which led to debates, for example by Albert Einstein who remained critical of the theory for the rest of his life (Golub & Lamoreaux, 2023). For instance, Einstein described entanglement as 'spooky action at a distance' (Einstein et al., 1971) and argued that quantum theory had therefore still to be incomplete (Einstein et al., 1935).

This first quantum revolution has led to the development of technology (such as smartphones, lasers and MRI scanners), because of *our understanding* of how nature works on the smallest scale. Currently we are in the *second quantum revolution*, which is about developing new technology by *manipulating* nature on the smallest scale (i.e., manipulating quantum effects to our own design; Dowling & Milburn, 2003). Three quantum effects that scientists are trying to manipulate to their own advantage in this second revolution are superposition, entanglement and contextuality (Grinbaum, 2017, but see Dowling & Milburn, 2003 for other key principles). Box 1 provides a brief overview of these three key quantum effects. By manipulating these effects, scientists are developing new technologies such as quantum computers, the quantum internet, and quantum sensors. These technologies will be briefly introduced in Section 1.1.1.

1.1.1 Technology of the second quantum revolution

The quantum computer

An expected technology of the second quantum revolution is the quantum computer. In contrast to the computers we use today (classical computers), which process information according to the rules of classical physics, quantum computers process information according to the rules of quantum physics. Instead of classical bits, which can take on the values of 0 or 1, quantum computers use the quantum version of bits: qubits. As a result, they are expected to outperform classical computers on certain tasks to a greater or lesser extent. For example, quantum computers are expected to help coordinate agendas (DiVincenzo, 2000) and develop new medicines (Outeiral et al., 2021), but they also have the potential to break our current encryption, which may enable criminals to access protected information (Vermaas et al., 2019).

At the time of writing, smaller quantum computers have already performed calcula-

Box 1: Superposition, Entanglement and Contextuality

Three quantum phenomena important in the development of quantum technology from the second quantum revolution are superposition, entanglement and contextuality. An explanation is provided below for each phenomenon, based on Nielsen and Chuang (2010) and G. Jaeger (2019).

- **Superposition:** A quantum particle that is in a superposition state can be in multiple states at the same time. For example, a quantum system can be in a superposition of states "0" and "1" at the same time. This contrasts with classical physics, where a system can only be in state 0 or state 1, but never both at the same time. Superposition is thus a quantum phenomenon with no counterpart in classical physics.
- **Entanglement:** Multiple entangled particles can share a superposition state. Measuring one of the particles instantly affects the state of the others, even when the particles are separated by a large distance. Quantum entanglement also has no counterpart in classical physics. In mathematical terms, particles can only be described by the quantum state for the entire system, and not by their individual quantum states.
- **Contextuality:** In quantum systems, the context of a measurement can influence its outcome. This means that the result of a measurement may depend on prior measurements performed on the quantum system. This contrasts with classical systems, where measuring one property - such as the width of a bicycle - always yields the same result, regardless of whether you first measured the length of the bicycle. Whereas measurements are thus non-contextual in classical systems, they are contextual in quantum systems. For physicist Niels Bohr, contextuality was a consequence of his principle of complementarity, which states that certain pairs of properties - such as position and momentum - cannot be simultaneously measured in a precise manner.

tions believed to be out of reach for current classical computers (see e.g., Acharya et al., 2025; Arute et al., 2019; Zhong et al., 2020, 2021). However, these calculations appear to be primarily of academic value, lacking practical applications (Roberson, 2021). Expectations for when quantum computers will have practical use vary. One estimate suggests that early quantum computers may already prove useful for tasks such as simulating certain materials or combining classical and quantum computers for optimization problems (Mohseni et al., 2017). In addition, the majority of experts surveyed by Mosca and Piani (2024) believe it is likely that a quantum computer will crack our current encryption method in the next 15 years.

The quantum internet

Another expected technology of the second quantum revolution is the quantum internet. In their vision paper, Wehner et al. (2018) describe the quantum internet as a new internet technology that should enable the transmission of qubits between any two places on the planet. The ultimate goal is a gradual move towards a network of large-scale quantum computers that can transmit an arbitrary number of qubits among each other. One of the main anticipated applications of the quantum internet is secure online communication - even in the presence of an eavesdropper or when the quantum device itself is considered untrustworthy. It could also eventually support applications such as online voting which is secure to malicious attacks. In addition, a risk includes law enforcement agencies losing their grip on terrorist organisations that use the technology to communicate, amongst other (see Vermaas et al., 2019).

At the time of writing, early quantum networks (i.e., trusted repeater networks) have already been tested in applications such as secure conferencing (Project UQCC, n.d.) and secure banking (Zhang, 2017). In the Netherlands, versions of these networks have been trialled in the Port of Rotterdam to securely exchange sensitive data between two places in the port (Port of Rotterdam, 2024). Progress has also been made toward more advanced stages of quantum networks (i.e., end-to-end networks) in lab-based settings. For instance, three quantum devices have been connected in a lab-based network (Pompili et al., 2021) and several research groups have connected two quantum devices over longer distances using existing underground optical fibers (Castelvecchi, 2024), such as over 25km across the Dutch cities Delft and The Hague (Stolk et al., 2024). One estimate from a Chinese research team is that, by 2030, they will be able to connect quantum devices over 1,000 km via optical fibers (Castelvecchi, 2024).

The quantum sensor

A third technology of the second quantum revolution is the quantum sensor. Quantum sensors can measure time, gravity or other physical quantities with, for instance, a quantum phenomenon such as entanglement (or with a quantum system or quantum property; C. L. Degen et al., 2017). This allows quantum sensors to outperform classical sensors, for instance in terms of accuracy of the measurement.

At the time of writing, commercial quantum sensors have already been shown to outperform classical sensors when measuring small, underground objects (Crawford et al., 2021; Stray et al., 2022). Stray et al. (2022), for instance, showed that their quantum sensor measured a 2-by-2 meter tunnel located about 0.5 meters underground more quickly and precisely than current classical sensors. They argued this finding is important for safety reasons, minimizing risks for unexpected ground conditions, when building energy and transportation infrastructure, amongst others. Furthermore, commercial quantum sensors have been developed for applications such as 3D terrain mapping, even underwater, and for monitoring greenhouse gas emissions (Crawford et al., 2021). In addition, quantum sensors may also raise ethical and privacy issues when used to monitor personal data, such as individuals' energy or water usage, or when large amounts of sensing data are not well protected (Chapman et al., 2024).

1.2 The field of science communication in quantum developments

1.2.1 Public engagement with quantum science and technology

Quantum technology from the second revolution is still largely in the early stages of development. Many of the applications that exist are still lab-based and have no real-world application yet. Although there are technological obstacles to the further development of quantum computers (Mohseni et al., 2017), quantum networks (Wehner et al., 2018), and quantum sensors (Kantsepolsky et al., 2023), the real-world applications are expected to have a significant impact on society in the future. Examples include new medicines (Outeiral et al., 2021), secure online voting (Wehner et al., 2018), and safer constructions of energy and transportation infrastructure (Stray et al., 2022), but also the breaking of our encryption that may enable data breaches (Vermaas et al., 2019), losing grip on criminal organisations (Vermaas et al., 2019) and ethical and privacy issues from large amounts of sensing data (Chapman et al., 2024).

While quantum technology is still in an early stage of development, the field of science communication provides several reasons to already engage societal actors. A contemporary definition of science communication is (Smeets et al., 2025, p 5):

> **Science communication** encompasses all the ways in which people outside of the scientific world could be engaged with scientific research. This could be listening to and looking at results of research, formulating research questions together or discussing the possible consequences of science. One can think of popular scientific lectures, TV shows, discussion panels or audience research.

The first reason to already involve a broader group of people early in the development of a new technology is that, according to Roberson et al. (2021), it can lead to more socially robust solutions to societal challenges. Although scientists often imagine the potential societal impact of the technologies they develop, involving a broader group of people allows for a broader perspective to be included in this imagination.

Second, involving society can result in greater support for, and less opposition towards, the technology. When compared with scientists, non-experts often have a different perception of risks and benefits and judge information based on other factors such as trust in the source, their own values and beliefs, and existing knowledge (Siegrist, 2010; Van Dam et al., 2020). For instance, in assessing the risk perception towards nanotechnology, laypeople were found to be more concerned about social risks such as job loss, whereas experts were more concerned about potential health and environmental risks (Siegrist, 2010). Furthermore, while scientists know the scientific facts, members of the public possess lay knowledge (Van der Sanden & Meijman, 2008). According to Van der Sanden and Meijman (2008), it is the task of science communication to clarify that lay knowledge. This would allow scientists to understand better if (and if yes, which) misconceptions form some of the starting points of the public's perceptions and expressions.

Third, public engagement is regarded as important for aligning new technology with societal values (Cath et al., 2018; Van Dam et al., 2020). This can be seen, for example, in the field of artificial intelligence (AI), where there is a call for greater public engagement (Cath et al., 2018). While transparency, such as disclosing information of source code and data use by AI developers, is the most commonly referenced value in reports and ethical guidance documents for AI (Jobin et al., 2019), in practice, private actors often keep such information to themselves. There are certainly examples about dialogue and deliberation with the public on AI, such as the Moral Machine experiment (Awad et al., 2018), but national agendas still primarily view the public as users of AI services or as members of a potential workforce – not as individuals who should be involved in aligning AI with societal values (Wilson, 2022). This example shows that, while developments in science and technology can have a major impact on people's lives, aligning new technology with societal values does not always appear to be a priority. To achieve such a proper alignment, public engagement is regarded as important (Cath et al., 2018).

To achieve meaningful public engagement, Reincke et al. (2020) have proposed three roles for experts, which can be extended to science communicators in general. The first role involves sharing information in a meaningful way. This means that senders should go beyond merely mentioning the benefits and risks of a technology, but they should also try to address its potential to personal relevance and the public good. The second role involves listening to and learning from others. This aligns with the notion that while scientists know the scientific facts, members of the public can possess valuable lay knowledge (Van der Sanden & Meijman, 2008). The third role is about investing in relationships with the public. To build trust, senders should try to show their expertise, but avoid becoming too scientific as this can create a sense of distance.

The information that is presented in public communication can thus contribute to creating a good connection between a new technology and society (see the first role proposed by Reincke et al., 2020). This dissertation focuses on this first role by specifically focusing on the role of two communication devices that can play a role in the process of engaging people with quantum technology: *frames* (section 1.2.2) and *metaphors* (section 1.2.3).

1.2.2 Frames

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). In this dissertation, we focus on emphasis frames which highlight various dimensions of an issue. For example, a 'benefit frame' focuses on the positive outcomes of a certain aspect, whereas a 'risk frame' emphasizes potential downsides. Such emphasis frames are seen as important in understanding how people form opinions based on the specific aspects of an issue they are confronted with (Brugman & Burgers, 2018).

Research on frames has shown that certain frames are common in topics related to science and technology, while others are issue-specific (Nisbet, 2009). An example of a frame that consistently appears in communication on science and technology is the economic development/competitiveness frame, which focuses on economic investment, market benefits or risks, and competitiveness at local, national, or global levels (Nisbet, 2009). In the context of new technologies, benefit and risk frames have been analysed frequently (Gurr & Metag, 2022). In contrast, an issue-specific frame is specific to a certain topic. For instance, in the context of quantum physics, an issue-specific frame is the enigmatic frame, which presents quantum physics or one of its applications as something mysterious (Coenen et al., 2022; Vermaas, 2017). Frames that are analysed frequently are useful to examine such that we can make comparisons between different topics over time, while issue-specific frames can provide deeper insights into the framing of a particular topic (Brugman & Burgers, 2018).

By highlighting certain aspects of information while omitting others, frames can shape how people perceive and understand that information (Entman, 1993). In the context of new technologies, exposure to certain frames has been shown to influence public attitudes toward these technologies (Achterberg, 2014; Bingaman et al., 2021; Cobb, 2005; Druckman & Bolsen, 2011). For example, an experimental study found that people expressed greater support for AI when they read about its benefits (increase safety, improve lives, and solve global problems), compared to when they read about its risks (poses dangers, disrupts lives, and could lead to humanity's downfall; Bingaman et al., 2021). The extent of a framing effect can, however, vary depending on several factors. Examples of factors include individual characteristics like trust in science and technology (Achterberg, 2014) and message characteristics such as whether a frame emphasizes specific risks or benefits versus broader ones (Cobb, 2005).

1.2.3 Metaphors

Metaphors are communicative tools that allow people to comprehend one concept (referred to as the target domain) in terms of a different one (referred to as the source domain; Lakoff & Johnson, 1980). Defined as 'cross-domain mappings' (Lakoff & Johnson, 1980), metaphors map information from a source domain onto a target domain. The source domain is usually more concrete, straightforward and familiar (such as a partner dance), while the target domain is generally more abstract and complex (such as entanglement). By choosing a particular source domain, metaphors make certain aspects more salient while automatically downplaying others. This illustrates that metaphors are also framing devices that can subsequently affect how concepts are perceived and understood.

In the context of science communication, metaphors generally function to make a scientific concept easier to understand (Beger & Smith, 2020; Smedinga et al., 2023), but metaphors may also lead to misinterpretation (Zook & Maier, 1994) and possible resistance from experts and non-experts (Brugman et al., 2022; Gibbs Jr & Siman, 2021). Resistance, for instance, occurs when experts feel that a metaphor does not sufficiently explain the scientific topic (Gibbs Jr & Siman, 2021). Gibbs Jr and Siman (2021) even put it that "one of the worst criticisms a scientist can make of a theory is that it is 'just metaphorical', which is tantamount to saying that the theory is false, unscientific, and of little practical value" (p 672). Non-experts may resist metaphors because the metaphor does not resonate with them (Brugman et al., 2022). While metaphors may thus be promising tools in science communication, there may also be limitations.

1.2.4 Call for research

The previous sections have highlighted the importance of creating a strong connection between quantum technology and society. This calls for research to improve our understanding of how to do so. There are concerns that the current communication around quantum technologies poses barriers for public engagement with quantum technology (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021; Seskir et al., 2023; Vermaas, 2017). Examples of possible barriers include famous physicists calling quantum mechanics 'spooky' (Einstein et al., 1971) and 'incomprehensible' (Feynman, 1967), national quantum agendas focusing on winning the quantum race (Roberson et al., 2021), and a focus on quantum computing at the expense of other quantum technologies (Roberson et al., 2021).

However, we do not know whether the concerns about the communication of quantum technology to a broader audience (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021; Seskir et al., 2023; Vermaas, 2017) are justified, because we have no insight into the occurrence of these possible barriers in public communication, nor do we know what the actual effect of these barriers is. For instance, it is unknown whether frames such as the spooky and enigmatic frame are common in communication about quantum technology targeted at a broader audience, nor do we know its effect on public engagement with quantum technology. The question furthermore arises whether certain communication devices can help to establish good connections between quantum and society – such as the use of metaphors in explaining quantum mechanics to make the topic more comprehensible. This dissertation addresses these issues.

1.3 Outline of the dissertation

This dissertation investigates the occurrence of two communication devices around quantum science and technology (frames and metaphors), and their influence on the public. It consists of the following chapters (see Figure 1.1 for a schematic overview):

- **Chapter 2** reports on a content analysis of 501 TEDx talks, focusing on four potential popularisation issues in quantum science and technology, as postulated in the literature. These issues are: 1) framing quantum science as spooky or enigmatic (Coenen et al., 2022; Vermaas, 2017), 2) skipping the underlying quantum phenomena when explaining what quantum technology entails (Grinbaum, 2017); 3) using a narrow instead of a wider public good frame (Roberson et al., 2021); 4) focusing on quantum computers at the expense of other quantum technologies, such as quantum networks and quantum sensors (Roberson et al., 2021). We begin by describing these potential issues in the popularisation of quantum science and technology and report on their frequency in TEDx talks. In addition, we examine differences between quantum experts and non-quantum experts. We discuss the implications of these findings for quantum experts when communicating their work to a broader audience.

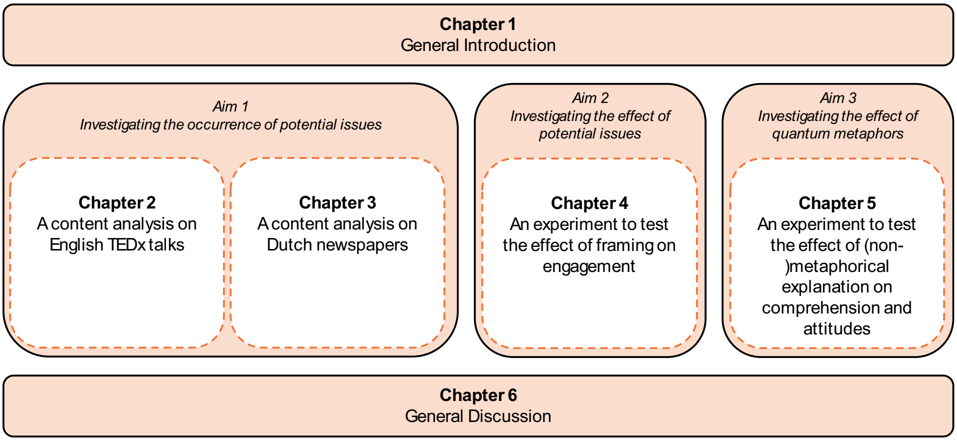
- **Chapter 3** further investigates the occurrence of potential popularisation issues in quantum science communication by analysing 385 Dutch newspaper articles. Implications for science communicators and journalists are discussed.

- After having quantified the occurrence of the potential issues in popular communication in the previous chapters, **Chapter 4** explores their effects on engagement with quantum technology. To keep the experimental design feasible, we concentrate on the first three potential issues: enigmatic framing, explaining quantum physics, and the balanced frame. Using an experiment involving $n = 637$ participants representative of the Dutch population, we examine how these communication characteristics influence public engagement with quantum technology. Practical advice is provided for science communicators in the field.

- **Chapter 5** explores how metaphorical and non-metaphorical explanations of superposition and entanglement in a news article affect comprehension and attitudes towards quantum technology. In an experiment involving $n =$ 1,176 participants, we investigate how two explanation types (metaphorical

Figure 1.1

Schematic overview of the dissertation.



and non-metaphorical explanations of a quantum phenomenon) influence perceived comprehension of the news article, actual comprehension of the quantum phenomena, affect-based attitudes towards quantum technology, and cognition-based attitudes towards quantum technology. We further investigate whether explanation types influence attitudes which is mediated by comprehension. We conclude with practical implications of the findings.

- **Chapter 6** provides a reflection on the work presented in this dissertation. We present an outlook on future research directions in the field, and offer recommendations for science communication researchers and science communicators based on the implications of this dissertation.

CHAPTER 2

Is Everything Quantum 'Spooky and Weird'? An Exploration of Popular Communication About Quantum Science and Technology in TEDx Talks

This chapter is based on: Meinsma, A. L., Kristensen, S. W., Reijnierse, W. G., Smeets, I., & Cramer, J. (2023). Is everything quantum 'spooky and weird'? An exploration of popular communication about quantum science and technology in TEDx talks. *Quantum Science and Technology*, *8*(3), 035004. https://doi.org/10.1088/2058-9565/acc968

Abstract

Previous studies have identified four potential issues related to the popularisation of quantum science and technology. These include framing quantum science and technology as spooky and enigmatic, a lack of explaining underlying quantum phenomena of quantum 2.0 technology, framing quantum technology narrowly in terms of public good and having a strong focus on quantum computing. Before assessing the effect of these potential issues on public perceptions, it is important to first determine whether these issues are actually present in popular communication. To this end, we conducted a content analysis in which we investigated how quantum science and technology are framed in a corpus of 501 TEDx talks. We also examined to what extent quantum experts, such as quantum scientists and leaders at organisations in quantum science and technology, communicate about quantum science and technology differently from non-experts, such as scientists from other

disciplines and artists. Results showed that: 1) about a quarter of the talks framed quantum science and technology as spooky/enigmatic; 2) about half of the talks explained at least one underlying quantum phenomenon (superposition, entanglement or contextuality) of quantum 2.0 technology; 3) quantum technology is narrowly framed in terms of public good as we found six times more talks mentioning benefits than risks; and 4) the main focus is on quantum computing at the expense of other quantum technologies. In addition, experts and non-experts differ on three out of four issues (only the fourth issue is similar for both). Our findings thus show that these potential issues related to the popularisation of quantum science and technology are present but not predominant in TEDx talks. Further research should explore their effect on public perceptions of quantum science and technology.

2.1 Introduction

In the 20th century, the first quantum revolution took off. Scientists started to understand and apply the laws of quantum physics, which led to ground-breaking technologies such as lasers and transistors (quantum 1.0 technology). The current second quantum revolution is expected to have an even bigger impact: by actively manipulating quantum effects in systems and materials, scientists are developing quantum technologies (quantum 2.0 technology) that might impact society at large (European Quantum Flagship, 2020; Stichting Quantumdelta NL, 2020; Vermaas et al., 2019). Most of these quantum 2.0 technology based devices have not been realised commercially yet, but are developed in a research setting. This makes it hard to predict the exact impact these quantum 2.0 technologies will have on society, although some benefits have been envisioned. One of these benefits is that quantum computers can impact drug discovery through the simulation of chemical systems (Mohseni et al., 2017; Outeiral et al., 2021). Moreover, the vision of the quantum internet is to enable quantum communication between any two points on earth enabling secure communication, among other things (Wehner et al., 2018). Thirdly, quantum sensors are expected to be useful devices in the development of transport and energy infrastructures, since these devices can measure very accurately what is happening underground and therefore identify risks to ground conditions (Stray et al., 2022).

Besides potential benefits, these new quantum technologies could also pose risks for our society. For example, an envisioned risk is that governments will lose their grip on criminal organisations that communicate via quantum networks (Vermaas et al., 2019). Unequal access to quantum computing between countries is another potential risk, making it unlikely that the benefits of the technology will be shared equally (Holter et al., 2022). Also, large enough quantum computers - although still very challenging to build - pose the risk of ‘breaking the Internet’: running a specific type of quantum algorithm, Shor’s algorithm, enables large enough quantum computers to break current encryption methods (Inglesant et al., 2021; Vermaas et al., 2019).

To maximise the societal benefits of quantum technology while minimising the risks it may pose, societal engagement could be key. One of the reasons for this is that societal engagement might lead to more socially robust solutions as a result of gaining a wider view on the impact of the technology on different social settings (Roberson et al., 2021). Several studies, however, expect problems due to potential issues in popularising quantum science and technology (Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021; Vermaas, 2017). To date, their occurrence has not been quantified. Therefore, the goal of our research was to investigate whether these problems are present in the context of a specific type of popular communication: TEDx talks. In these talks, speakers share their research and ideas in order to spark conversations within local communities. Given that TEDx events invite a variety of speakers (TED, n.d.-a), we have also compared the communication of quantum experts to that of non-experts. The next section presents our theoretical framework that includes the relevant literature on which our study is based.

2.2 Theory

2.2.1 The importance of connecting with societal actors in the development of emergent technologies

Science communication scholars agree that it is important to connect to the public in an early stage of a technology's development (i.e. upstream engagement; Kurath & Gisler, 2009; Mooney, 2010; Priest, 2010). Arguments include that: 1) engaging societal actors could allow for more social contexts to shape an emergent technology (Roberson, 2021); 2) engagement could lead to more public support and less public resistance (Kurath & Gisler, 2009; Mooney, 2010; Roberson et al., 2021); and 3) public engagement fits a democratic point of view (Van Dam et al., 2020). This section briefly highlights each of these arguments.

First of all, according to Roberson (2021), engaging societal actors could allow for more social contexts to shape an emergent technology as well as give a broader overview of the technology's impact on different social settings. Upon designing an emergent technology, the scientists, who operate in social contexts themselves, mainly imagine the use and impact of the technology they are building. Their social contexts therefore have a great influence. If different societal actors would engage in an emergent technology's development, more social contexts could shape these imaginations.

Secondly, involving society can lead to more support and less public resistance (Kurath & Gisler, 2009; Mooney, 2010; Roberson et al., 2021). The history of science communication of emergent technologies reveals that some of the previous emergent technologies have had to deal with public resistance (Kurath & Gisler, 2009) and did not always lead to public benefit (Roberson et al., 2021). For instance, Roberson et al. (2021) describe an example of a new technology in agriculture, developed in the 1950s in the United States, that caused more than 80% of tomato-growing businesses to go into bankruptcy within 5 years of the technology's adoption. Businesses without adequate amounts of land were not able to benefit from the new technology. This prompted a public debate with civil society organisations about whose needs and desires the researchers were addressing and whose were not.

The third argument is normative in nature. From a democratic point of view, citizens should be allowed to express their opinions and concerns about developments that largely impact their lives. Since science and technology developments can have a great impact on citizens' lives, they should be allowed to participate in the decision-making process (Van Dam et al., 2020).

According to Reincke et al. (2020), experts have a number of responsibilities in engaging the public in science, which include sharing input. Experts should share information in a meaningful way, such that the public feels empowered to participate in further engagement. This includes the fact that not merely the risks and benefits of a technology should be discussed, but also its potential for personal relevance and public good (Busby et al., 2017; Reincke et al., 2020). Ensuring that the public has access to meaningful information is a first step toward high-quality public engagement, even though it is not sufficient in and of itself (Priest, 2010). In this study, we focus on the sharing of input by analysing how information about quantum science and technology is communicated in TEDx talks. The TEDx platform is a very suitable source as it aims to spark conversation within local communities across the world through knowledge sharing (TED, n.d.-a).

2.2.2 Science popularisation in TEDx talks

The process of science popularisation often involves a re-contextualisation of scientific knowledge by 'making the vocabulary plainer and more intelligible and adapting the content to the public's prior knowledge and immediate information needs' (Mattiello, 2017, p 78). Popular communication about quantum science and technology has already been explored in different contexts, such as in popular science books (Dihal, 2017), documentary films (Gaunkar et al., 2022) and games (Seskir et al., 2022). One specific form that to our knowledge has not yet been investigated is the TEDx platform.

In TEDx events, speakers from the community with different backgrounds and expertise are invited to present their research and ideas in under 18 min to the local community (TED, n.d.-b). This platform thereby allows speakers to talk directly to their local audience without a mediator in between. The events are very similar to TED events (Technology, Entertainment and Design), but a difference is that TEDx events are always locally organised. In addition to taking place in a local venue, the talks are freely accessible to web users (TED's secondary participants; Mattiello, 2017) via the TEDx channel on YouTube.

2.2.3 Potential issues in popularising quantum science and technology

In this work, we analysed the framing of quantum science and technology in popular science communication. 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). Highlighting particular parts while neglecting other parts of some information can have a big effect on how the audience perceives and understands this information (Entman, 1993).

We base our research on four potential issues that previous (theoretical) research has suggested to occur in the popularisation of quantum science and technology. These are: 1) framing quantum science and technology as spooky and enigmatic (Vermaas, 2017); 2) the use of a pragmatic approach when explaining quantum 2.0 technology (Grinbaum, 2017); 3) the use of a narrow public good frame in relation to quantum technology (Roberson et al., 2021); and 4) the strong focus on quantum computing (Roberson, 2021).

Spooky and enigmatic frame

The first potential issue in popular communication about quantum science and technology is the framing of quantum science as enigmatic (Coenen et al., 2022; Vermaas, 2017) and spooky. An example of the latter is a phrase coined by Einstein, who referred to the quantum mechanical concept of entanglement as 'spooky action at a distance' (translated from German *spukhafte Fernwirkung*) in one of his letters to Max Born (Einstein et al., 1971).

According to Vermaas (2017), a possible consequence of framing quantum science as enigmatic is that it can hinder societal actors to join in on public debates. He supports moving away from enigmatic metaphors like Schrödinger's cat (i.e. a hypothetical cat that is in a combined state of being dead and alive to depict the concept of superposition) and from saying that quantum theory is counterintuitive in nature. Instead, it should be introduced as a novel information theory and the technological effects it might have should be presented (Coenen et al., 2022; Vermaas, 2017). The question arises whether the spooky and enigmatic frame is indeed widely present in popular communication about quantum science and technology.

Using a pragmatic approach for explaining quantum 2.0 technology

A second potential issue is how quantum 2.0 technology is explained in popular communication. We use the following definition of what constitutes an explanation: 'Explanatory discourse, (...), is premised on the assumption that readers are aware of some phenomenon such as light or language dialects but do not fully understand that phenomenon's nature. Thus explanatory discourse tries to promote or create understanding for lay readers of some phenomenon' (Rowan, 1988, p 16).

Grinbaum (2017) states that popular and semi-popular accounts of quantum science and technology currently use a 'pragmatic approach' when explaining quantum 2.0 technology. Such an approach skips over the explanation of underlying quantum phenomena, but instead focuses on protocols and how these are building blocks for quantum 2.0 technology. While such a pragmatic approach is an efficient short-cut, there are some drawbacks associated with it as well. For example, it does not allow the public to experience the beauty of quantum theory (something that quantum physicists experience when working with the mathematics of it), while Grinbaum (2017) argues this experience is necessary for the public to gain trust in quantum technology. Grinbaum (2017) proposes that narratives could be a solution and states that 'constructing a narrative that conveys scientific content as well as provoking a feeling of beauty is the hard problem in the relations between science and society' (p 304).

To our knowledge, no research has been performed yet to establish whether popular and semi-popular accounts indeed skip over the explanation of underlying quantum phenomena when explaining quantum 2.0 technology. For physics in general, Kristensen et al. (2021) found that in Dutch news articles physics is explained in many different ways. For example, sometimes the focus is on the causal factors, sometimes it is about what the function or application of a concept is, and analogy is another type of explanation. The question arises if the fundamental quantum phenomena on which quantum 2.0 technology is based are explained in popular and semi-popular accounts.

Narrow vs wider public good frame, benefit vs risk frame

A rhetorical analysis of the national quantum strategies of the US, the UK and Canada points out a third potential issue where a dominant frame about 'winning the quantum race' and realising economic development (the economic development/competitiveness frame) was found (Roberson et al., 2021). The Canadian national quantum strategy, for example, emphasises that nations are 'racing to develop technologies that can deliver incredible capabilities which will far exceed those of conventional technologies' (Roberson et al., 2021, p 5). Roberson et al. (2021) argue that such a frame is narrow in the sense that the uses and implications of quantum technology in and on society are not reflected upon more widely.

Roberson et al. (2021) encourage quantum physicists to use a wider 'public good' frame, i.e. a wider reflection of how quantum research could benefit and harm society. Examples of a wider public good frame have been found in the rhetoric of quantum physicists during the conference *Project Q* in 2019 that focused on political implications of quantum technology. Quantum physicists have said to be mainly 'driven by goals of improving the society we live in' and are 'trying to solve problems in health, energy, [and] climate change' (Roberson, 2021, p 109), thereby framing their motivation in terms of social progress.

Both the economic development/competitiveness frame as well as the social progress frame are frames that have consistently recurred in science and technology debates (Nisbet, 2009), for example in artificial intelligence (AI). Cave and ÓhÉigeartaigh (2018) have assessed the risks of using the competitiveness frame (i.e. 'winning the AI race') and argue the frame is not beneficial for an inclusive, multi-stakeholder discussion on how AI can provide societal benefits while minimising risks. The social progress frame is presented as one of the alternatives that could counteract the risks the competitiveness frame poses (Cave & ÓhÉigeartaigh, 2018).

Besides focusing on the benefits for society, a wider public good frame also includes a broader reflection on the risks. Many studies have already investigated how new technologies are framed in terms of benefits and risks (e.g., Gurr & Metag, 2022), as these frames can influence the perception of societal actors towards a new technology (e.g., Achterberg, 2014; Cobb, 2005; Druckman & Bolsen, 2011). Gurr and Metag (2022) found that the use of the benefit and risk frame vary depending on the technology, time period and media being analysed. For example, the frames most prominent in news media about nanotechnology are medical, scientific and economic benefits; carbon capture and storage is frequently framed in terms of political/legal and economic risks and benefits; and for synthetic biology, energy benefits are often mentioned (Gurr & Metag, 2022). To our knowledge, it has not yet been explored how quantum technology is framed in terms of benefits and risks.

A focus on quantum computing

To realise a wider public good frame, Roberson et al. (2021) suggest to focus on a wider range of quantum technology applications. This is in contrast to only focusing on the quantum computing applications of national security risks (e.g. decrypting public key cryptography) and realising economic development (e.g. big data in finance, to help calculate investment risks). In semi-structured interviews with four quantum physicists, who played important roles in designing visions for the national strategies of their countries, a focus on quantum computing got mentioned as well. One of them said that ‘our field is broader than quantum computing: quantum tech is much broader’ (Roberson et al., 2021, p 5). Whether or not there is a focus on quantum computing in TEDx talks is an open question.

Differences in the use of frames between science experts and non-experts

Experts and non-experts might differ in how they frame and approach their communication about emergent technologies towards a general audience (Droog et al., 2020; Priest, 2010). In a study on cyberinfrastructure for big data, a specific emergent information technology, Droog et al. (2020) analysed the metaphorical framing of that technology by experts involved in cyberinfrastructure development (e.g. technological developers and supercomputing centre administrators) and non-expert journalists. They analysed the use of metaphors in 15 US news texts (journalists) and 147 interviews with experts and found profound differences between both groups. An example of a difference is that most experts use precise metaphorical frames (e.g. a precise metaphorical frame that contains the word ‘tool’ specifies the type of tool, e.g. a hammer or a Swiss army knife), while the frames used by most journalists tend to be unprecise (e.g. an unprecise metaphorical frame that contains the word ‘tool’ does not specify which tool is referred to).

To examine whether differences between quantum experts and non-experts occur in popular scientific communication about quantum science and technology, we examine how often they use the four potential issues presented in section 2.2.3.

2.3 Methods

The primary research question our study addresses is:

> *Research Question 1:* How are quantum science and technology popularised in TEDx talks?

We investigated the following sub-questions:

(a) How often are quantum science and technology framed in terms of being spooky and enigmatic?

(b) When quantum 2.0 technology is mentioned, how often are the underlying quantum phenomena explained on which the technology is based?

(c) How often are quantum science and technology framed in terms of economic development/competitiveness and social progress?

(d) How often are quantum science and technology framed in terms of benefits and risks?

(e) Which quantum technologies are mentioned most often?

(f) How does the popular communication about quantum science and technology of quantum experts and non-experts compare?

Because we are interested in analysing the different frames used to describe quantum science and technology in popular communication, we performed a content analysis on TEDx talks that cover quantum science or technology. This research method allows for a 'systematic, objective, quantitative analysis of message characteristics' (Neuendorf, 2017, p 1). By following a standardized procedure which includes a codebook design and reliability testing, this research technique is expected to produce both replicable and valid results that are independent of the researcher (Krippendorff, 2019, p 24).

2.3.1 Data selection

Figure 2.1 shows the sequence of our data collection. On 18 May 2021, we searched for videos containing the keyword 'quantum' in the TEDx channel on YouTube by making use of the YouTube Data Application Programming Interface (API) v3 (Google Developers, n.d.). Since this API returns at most 500 videos per search, we performed individual searches per year. With 12 individual searches between 2009 (the year TEDx launched) and 2021, we acquired a total number of 4427 TEDx talks.

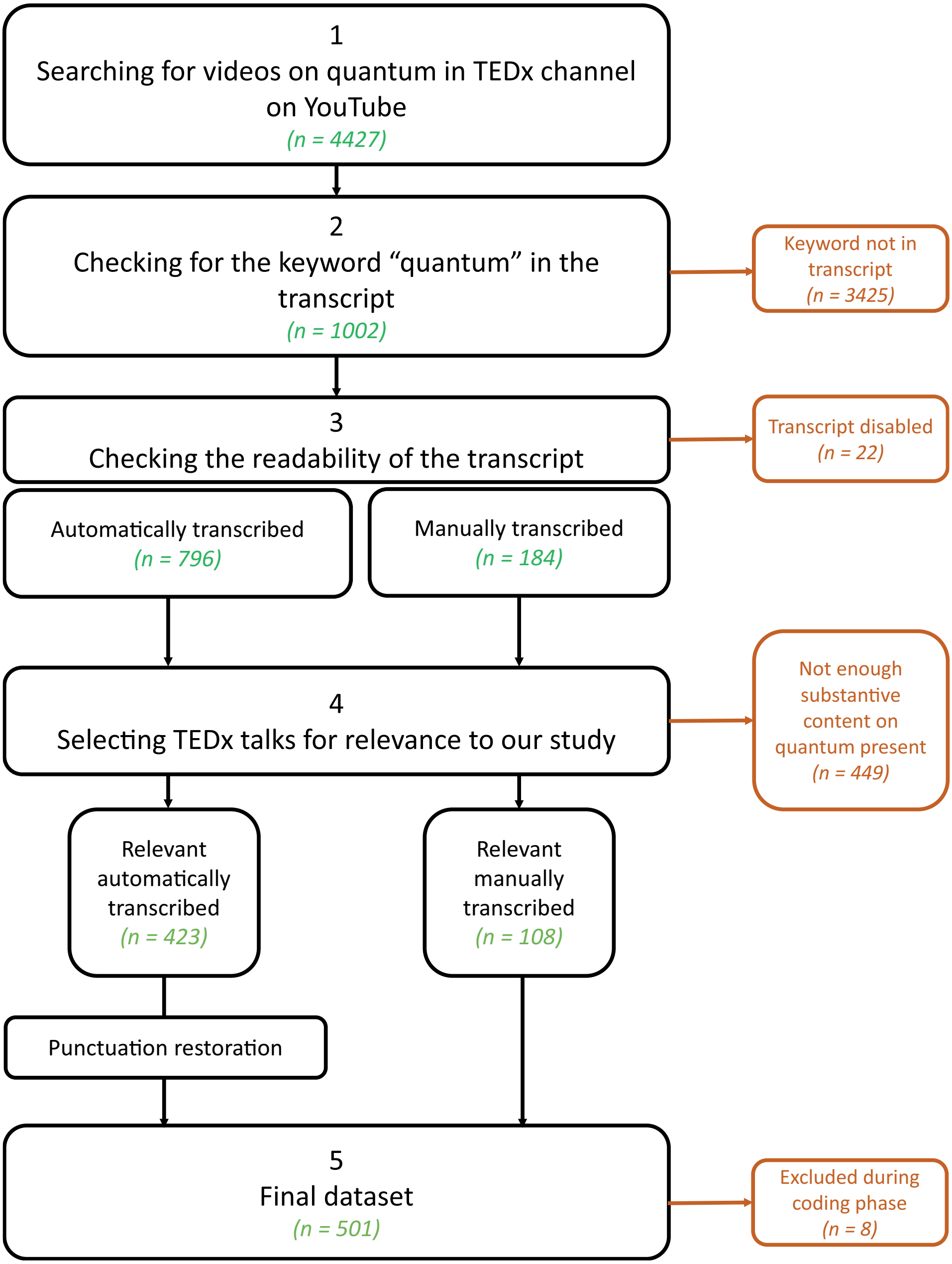
We downloaded all the transcripts of the collected TEDx talks and checked whether each transcript contained our keyword 'quantum'. Whenever the keyword could not be found, we deleted the transcript. This resulted in a total of 1002 transcripts.

Some of the talks had a transcribed or reviewed translated transcript which we refer to as 'manually transcribed'. Other transcripts had either been automatically generated by YouTube and therefore lacked punctuation, or had no English transcription available. We discarded those transcripts without an English transcription, leaving 796 automatically and 184 manually transcribed talks.

In the final step, we manually checked the transcripts for relevance to our study. When the transcript included enough substantive content about quantum science or technology, we included it in our final dataset. For example, when 'quantum' was

Figure 2.1

Data collection method.



used in 'quantum leap' or 'quantum jump' (to denote sudden change or stepforward) but with no reference to quantum physics or quantum technology, we deleted the transcript from our data set. Table A1 in the Appendix gives an overview of the reasons to discard transcripts. A second coder went through 10% of the data to check for relevance of the transcripts to our study, which resulted in an acceptable agreement (α = 0.79, 89.8%) between the two coders (Krippendorff, 2004).

2.3.2 Coding

The coding consisted of two phases based on predefined codebooks. Phase 1 focused on obtaining the descriptive data of the TEDx talk and identifying the quantum expertise of the speaker at the time of the talk, for which the YouTube descriptions were consulted. We defined quantum experts as scientists (undergraduates and graduates excluded) and leaders (e.g. founders, directors, CEO's, etc.) at an organisation who are working in or have worked in the field of quantum nanotechnology or another field in which quantum science plays a role. Examples of non-experts include scientists from other disciplines, artists and high school students. For a complete list of the various professions that were classified as quantum experts and non-experts, we refer to the codebook in Appendix A1.5. If the speaker's quantum expertise could not be determined based on the YouTube description we categorized them as 'quantum expertise unknown'.

Phase 2 focused on the content of the talks, based on the YouTube transcriptions. We first identified whether quantum science and/or technology was the talk's main focus, whether the talk included a holistic viewpoint (i.e. mystical ideas related to quantum physics, often pointing out that quantum physics tells us that everything is interconnected) and if a quantum 2.0 technology indicator (i.e. a term related to quantum technology of the second quantum revolution, for example quantum computer) was present in the transcript.

Secondly, for each talk we identified the occurrence of quantum applications. Specifically, we identified five quantum 1.0 technologies and three quantum 2.0 technologies. Whenever an application did not fall into one of the categories or remained unclear based on the text, the application was coded as other/unidentified. Subsequently, the specific frames that form the focus of our study were identified (i.e. the spooky and enigmatic frame, the social progress frame, the economic development/competitiveness frame, the benefit frame and the risk frame), and the accompanying quote was registered in the coding scheme.

Finally, we identified the presence of specific quantum science explanations, namely those mentioned by Grinbaum (2017) as theoretical notions underlying quantum technology[1]. These are 1) superposition, which means that a particle can be in a linear combination of states, e.g. an electron in a superposition state can simultaneously exist in spin states up and down; 2) entanglement, which means that two particles can share a strong connection with each other such that it no longer makes sense to talk about these two particles as being separate; and 3) contextuality, which means that performing a measurement on a quantum state irreversibly affects the state. The content of the explanations was based on definitions taught in physics education (Griffiths, 2014; Nielsen & Chuang, 2010) and coded by two physicists. The full codebook is available in Appendix A1.5. To test and improve the initial codebooks, TEDx talks from 2021 ($n = 22$) and 20 TED talks with quantum science and technology content that were not part of our final dataset were used for a pilot study.

2.3.3 Intercoder reliability

Inherent in doing content analyses is a degree of subjectivity, which we tried to overcome as best as we could by using a second coder. To determine the reliability of our final codebooks, two coders (the first and second authors of this paper) independently went through 15% of the final dataset (76 YouTube descriptions and transcripts). In phase 1, we found an acceptable agreement between the two coders (α = 0.78, 88.6%) for identifying speakers' quantum expertise and profession. Because reliability remained relatively low in the pilot study for phase 2, the first and second coder discussed their independent codings of the final dataset to reach agreement. Before the discussion, percent agreements between 80% and 100% were achieved, except for the codes on establishing if the TEDx talk had a 'quantum' focus (78%) and determining the use of the benefit frame (61%). Even though most codes achieved high percent agreements, Krippendorff's α remained low for some of them. We think this is caused by the low number of times that those codes appeared in talks (see Table A3 in the Appendix), meaning that a slight difference in interpretation between the first and second coder is already detrimental for α. By further refining the codes and with the discussion in mind, the first coder went through the remaining 85% of the transcripts.

[1]Grinbaum (2017) also mentions discord and steering as theoretical notions, but we decided to exclude these concepts from our final codebook for the following reasons: 1) the coders found no reference to or explanation of these concepts in the pilot study; and 2) when performing a search through the final dataset for the words 'discord' and 'steering', discord yielded 0 hits and only 2 hits for steering which—upon closer inspection—showed to be unrelated to quantum steering.

2.4 Results

2.4.1 Descriptive data

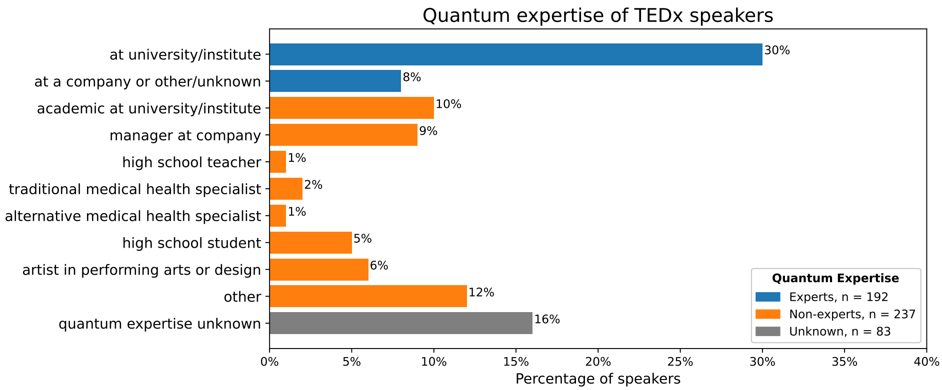
The 501 TEDx talks in our dataset were performed at TEDx events all over the world with a total of 55 different countries present in our dataset. Most talks were given in North America (*n* = 222 talks, 44%) and Europe (*n* = 173 talks, 35%) (see Figure A1 in the Appendix). The talks lasted between 3:49 min and 33:19 min and included the word 'quantum' eight times on average (the median is 3). Almost half (*n* = 236, 47%) of the 501 TEDx talks had quantum science and/or technology as their main focus. Furthermore, 73 talks (15%) included a holistic or mystical viewpoint. For example, one of the speakers mentioned that quantum physics is related to mental telepathy (TEDx Talks, 2016b, 12:11):

> [..] over the years I've been exposed to things like quantum physics, something known as the Morphogenic field, the field of our mind, expanding far beyond our brains, a kind of mental telepathy that says there could be a tipping point that if just one more person on the planet picks up a peaceful practice, and that person could be here in this room today, that there would be an instantaneous shift in everyone's awareness and the peace from our individual hearts would be communicated directly from mind to mind to mind spontaneously to everyone, everywhere on the planet.

Additionally, we identified the profession and the quantum expertise of the speakers at the time they presented the talk. In total, 23 speakers gave 2 or more TEDx talks, and expertise was coded by talk. Generally, the talks were given by one speaker (*n* = 490, 98%), but 11 talks (2%) were given by two speakers (expertise was coded for each speaker). As a result, we identified the expertise of 512 speakers. The majority of speakers were non-experts (*n* = 237, 46%), followed by quantum experts (*n* = 192, 38%). There were also relatively many speakers whose expertise we were not able to identify ('unknown', *n* = 83, 16%). Figure 2.2 shows the professions of the speakers and their related quantum expertise category in more detail. Most quantum experts (*n* = 153, 30%) worked at a university, institute or (inter)national research organisation. Non-quantum experts had a main expertise domain outside quantum science, for example an academic working in a different research field than quantum science. Perhaps somewhat unexpectedly, one of the non-quantum experts was even a shepherd from Pashmina, India.

Figure 2.2

The percentage of TEDx speakers per profession and related quantum expertise.



2.4.2 The spooky and enigmatic frame

The first frame that we analysed is the spooky and enigmatic frame. We found that the frame is apparent but not dominant in our dataset: 115 talks (23%) framed quantum science (applications) as spooky or enigmatic or as a synonym of these terms. Synonyms of spooky and enigmatic that occurred frequently are ‘strange’, ‘weird’ and ‘crazy’, such as in the following examples: ‘Now the quantum world is a really strange place’ (TEDx Talks, 2013, 3:49), ‘Everything "quantum" is spooky and weird’ (TEDx Talks, 2017, 8:06) and ‘I will try to introduce you in a crazy way to this crazy world of quantum computers and of quantum properties’ (TEDx Talks, 2018, 2:32). Also, Einstein’s well-known phrase came up, such as ‘Einstein, he called this spooky action at a distance’ (TEDx Talks, 2012b, 3:06).

2.4.3 Explanation of underlying quantum phenomena when mentioning quantum 2.0 technology

We established whether talks included a reference to quantum 2.0 technology, i.e. applications from the second quantum revolution such as quantum computers and quantum networks ($n = 127$). If so, we checked whether an underlying quantum phenomenon (superposition, entanglement or contextuality) was explained. In more than half of the quantum 2.0 technology talks we found an explanation of at least one underlying quantum phenomenon ($n = 69$, 54% of the quantum 2.0 talks).

Out of the three quantum phenomena that we studied, superposition was explained most often ($n = 57$, 45% of the quantum 2.0 talks) followed by entanglement ($n = 32$, 25% of the quantum 2.0 talks) and contextuality (*n* = 31, 24% of the quantum 2.0 talks). An example of a superposition explanation is 'If I make this ball quantum, [...], my quantum ball can be red or it could be blue or it can be red and blue at the same time. [...] it is a little weird, but we call it the superposition' (TEDx Talks, 2019, 5:10). Secondly, an example of an entanglement explanation is 'What happens if I take two of these quantum balls and I put them in a special kind of superposition state that I am going to call an entangled state. Well, this leads to some very strong correlations between the two balls, so strong, in fact, that it no longer makes sense to talk about them as separate objects' (TEDx Talks, 2019, 5:54). Thirdly, an example of a contextuality explanation is 'But what happens if I try to look at this quantum ball? Well, it turns out that I, as a classical observer, cannot actually view the superposition, but very actively trying to look at the ball forces it to be either red or blue' (TEDx Talks, 2019, 5:37).

2.4.4 The economic development/competitiveness vs social progress frame, and benefits vs risks frame

Besides the spooky and enigmatic frame, we analysed four more frames: the economic development/competitiveness frame, the social progress frame, the benefit frame, and the risk frame. Although holistic talks (*n* = 73, 15%) were found to frame quantum science and technology in terms of benefits, social progress and risks, they were unrelated to our research question. We therefore excluded the holistic talks from this part of the analysis. Consequently, the percentages presented in this section are with respect to the therefore relevant dataset (*n* = 428 talks). Table 2.1 gives an overview.

In our dataset, the amount of talks that mention the economic development/competitiveness frame (*n* = 23, 5%) was slightly lower to that of the talks with the social progress frame (*n* = 31, 7%). Of those, three talks included both frames simultaneously (1%). Examples of the economic development/competitiveness frame include 'quantum mechanics based products and services represent about more than one fifth of our gross national product' (TEDx Talks, 2009, 15:20) and 'there is a massive race toward building a new technology called quantum computing' (TEDx Talks, 2015, 3:19). An example of the social progress frame is 'I am going to tell you about how to make the world a better place with quantum mechanics' (TEDx Talks, 2016a, 00:09).

A difference is more apparent between the benefit and risk frames: over six times more talks included the benefit frame (*n* = 146, 34%) compared to the risk frame (*n* = 22, 5%). A balanced view was provided (i.e. both frames present simultaneously)

Table 2.1

Frequency table of the talks that include the economic development/competitiveness frame, social progress frame, benefit frame, and risk frame.

Frame	Total number of talks	Percentage of relevant dataset
Economic development / competitive-ness	23	5%
Social progress	31	7%
Benefit	146	34%
Risk	22	5%

Note. Multiple frames can appear in a talk. The percentages provided are with respect to the hereby relevant dataset (total dataset with the holistic talks excluded, n = 428 talks).

in 15 talks (4%). Benefits were most often mentioned in the life sciences & health field (n = 52, 12%), followed by energy & climate (n = 46, 11%). The security & privacy field was mentioned most often (n = 16, 4%) when a speaker highlighted a risk. In the Appendix, Figure A2 shows an overview of the percentage of talks with the benefit and risk frame in specific fields.

2.4.5 Technology applications of quantum science

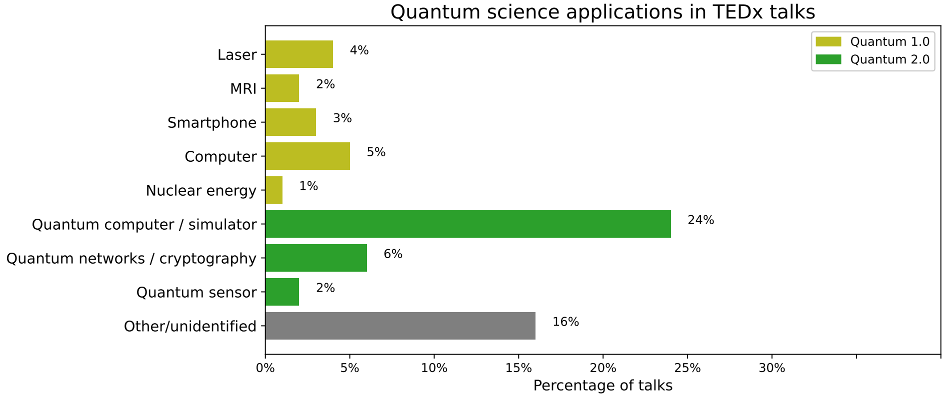
In our total dataset, 197 talks (39%) mentioned at least one technology application of quantum science. Quantum computers and simulators were mentioned most often as technology applications of quantum science (n = 120, 24%), followed by quantum networks and cryptography (n = 30, 6%), and classical computers (n = 25, 5%). An overview is presented in Figure 2.3, where quantum 1.0 refers to applications from the first quantum revolution, such as lasers and smartphones, and quantum 2.0 refers to applications from the second quantum revolution (quantum 2.0 technology). The other/unknown category (n = 82, 16%) contains technologies with a link to quantum science that we identified qualitatively. The top 3 applications that we identified in this category are transistors (n = 18, 4%), the scanning tunnelling microscope (n = 10, 2%) and solar cells (n = 6, 1%).

2.4.6 Comparison between quantum experts and non-experts

To establish whether there are any differences between popular communication by quantum experts (n = 192) and non-experts (n = 237), we did a comparative analysis. The group for which we were not able to determine the speaker's expertise was

Figure 2.3

The percentage of quantum science applications mentioned in TEDx talks.



excluded from this comparison. The differences between the groups are tested for significance with a chi-square test. Note that this analysis only gives an exploratory view since there is a dependence between the data points.

First of all, experts (*n* = 58, 30% of the experts) framed quantum as spooky or enigmatic more often than non-experts (*n* = 39, 16% of the non-experts) ($\chi^2(1) = 11.456, p < 0.001$).

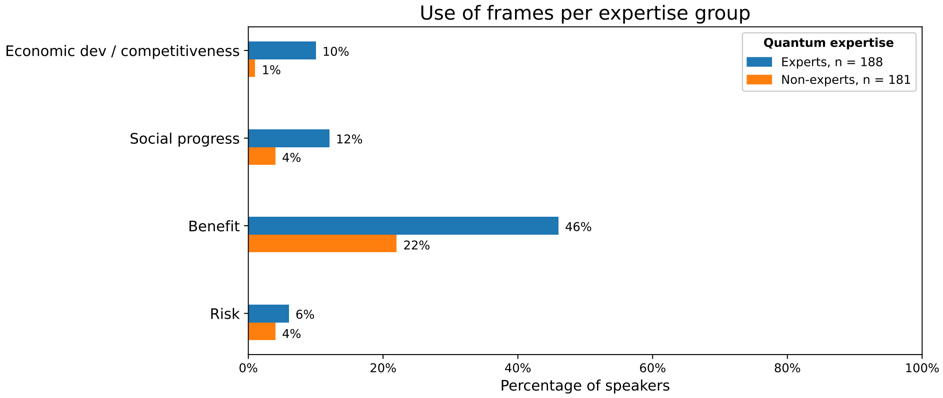
Secondly, there is a difference between the expert and non-expert group in explaining underlying quantum phenomena when mentioning quantum 2.0 technology. Although 70% of the experts (*n* = 52 out of 72) that mention quantum 2.0 technology provided an explanation of at least one of the quantum phenomena that we researched, only 28% of the non-experts (*n* = 13 out of 47) that mention quantum 2.0 technology did so. This difference between the groups is statistically significant, as confirmed by a chi-square test ($\chi^2(1) = 20.992, p < 0.001$). Figure A3 in the Appendix provides a comparison between the groups per quantum phenomenon explanation (superposition, entanglement and contextuality).

We furthermore analysed whether experts and non-experts used the economic development/competitiveness, social progress, benefit and risk frames in relation to quantum science and technology. In this comparison, we again excluded the speakers that expressed holistic views in their talk (4 experts and 56 non-experts) resulting in a total of 188 experts and 181 non-experts to compare. Figure 2.4 shows that experts used all these frames more often than non-experts did[2].

[2]We performed a chi-square test to test for significance for the data in Figure 2.4 (with mutually

Figure 2.4

The percentage of speakers per expertise group that use the economic development/competitiveness frame, the social progress frame, the benefit frame and the risk frame. Speakers that expressed holistic views in their talks are excluded from this comparison.



Finally, the quantum computer / simulator was the most often mentioned quantum science application for both experts ($n = 71$, 37% of their talks) and non-experts ($n = 43$, 18% of their talks). For both groups, there is a big gap to the second most often mentioned application ($n = 24$, 13% of the experts and $n = 5$, 2% of the non-experts mentioned quantum networks/cryptography).

2.5 Discussion

In this study, we explored the occurrence of potential popularisation issues with quantum science and technology in TEDx talks. To the best of our knowledge, this is the first study that quantitatively assessed whether the four potential issues suggested in the literature are present in a type of popular communication towards a broader audience.

2.5.1 Spooky and enigmatic frame: apparent but not dominant

The spooky and enigmatic frame is apparent but not dominant. It was the second most frequently occurring frame in our study, with almost a quarter of all TEDx talks in our corpus framing quantum science (applications) as spooky or enigmatic

exclusive categories), but these test results are less reliable due to multiple cells having expected counts less than five.

or a synonym of these terms. As such, this finding can be considered to provide some support for Vermaas' (2017) claim that quantum science is typically framed as enigmatic. At the same time, however, this frame did not occur in the majority of the analysed TEDx talks, and is therefore not dominant. From this perspective, our findings line up with those of Busby et al. (2017), who found that participants in a UK public dialogue exercise did not describe quantum science or technology as spooky or weird.

Our findings show that experts use the spooky and enigmatic frame statistically more often than non-experts. In order to explain this result, we looked for a link with Albert Einstein's well-known framing of quantum entanglement as 'spooky action at a distance' which experts might be more familiar with than non-experts. The specific phrase, however, was only used in 18 of the 115 talks that referred to the spooky and enigmatic frame (11 experts, 5 non-experts and 2 unknown). Therefore, we cannot identify this phrase as the main cause of the difference. Future research could delve deeper into this framing difference between experts and non-experts.

A first step to gain further insights into the prevalence of the spooky and enigmatic frame is to include an analysis of frames that can be seen as the positive counterparts of spooky and enigmatic, such as quantum science as an ordinary, comprehensible theory. Such an additional analysis could show whether experts and non-experts really present a different (i.e. more negative vs more positive) view on quantum science and technology. Furthermore, the research method that we chose can only describe what the 'product' (i.e. TEDx talks that cover quantum science and technology) looks like. We cannot draw conclusions about the speaker's motivations for using certain frames, nor can we discuss how these frames affect the audience's perceptions of, and actual engagement with, quantum science and technology. Therefore, future research could also investigate experts' and non-experts' motivations for using the spooky and enigmatic frame, as well as the public's reactions to it.

2.5.2 Explanations of underlying quantum phenomena: mostly given by experts

Over half of the talks included an explanation of at least one underlying quantum phenomenon (superposition, entanglement or contextuality) when quantum 2.0 technology was mentioned. On the one hand, this percentage is higher than expected given Grinbaum's (2017) claim that popular and semi-popular accounts of quantum science and technology skip over explaining underlying quantum phenomena when explaining quantum 2.0 technology. This conclusion is consistent with the fact that TED speakers re-contextualise scientific knowledge by explaining concepts in understandable language to their audience (Mattiello, 2017). The amount of time available could also play a role: TEDx talks generally last around 18 min, which gives speakers quite some time to delve into a topic. On the other hand, a substantial amount of the TEDx talks that mention quantum 2.0 technology did not provide an explanation of underlying quantum phenomena. Perhaps, providing these explanations is too technical after all and therefore less relevant for TEDx talks, especially when quantum phenomena are not the main topic.

The comparison between quantum experts and non-experts sheds further light on this finding: while Grinbaum's (2017) claim holds true for non-experts, it does not hold true for experts. The question arises whether non-experts make use of different explanatory tools when mentioning quantum 2.0 technology, as physics tends to be explained in many different ways (Kristensen et al., 2021). This is a limitation of our approach: we only looked for three pre-defined quantum phenomena, while undoubtedly, other interesting quantum phenomena are explained as well in communication about quantum science and technology. This calls for a qualitative bottom-up analysis of all explanations that are provided by both experts and non-experts to go beyond the three pre-defined quantum topics.

2.5.3 Narrow vs wider public good frame: over six times more benefits than risks

The social progress frame (a wider public good frame) occurred slightly more often (7%) than the economic development/competitiveness frame (a narrow public good frame; 5%). Despite the fact that both of these frames are listed by Nisbet (2009) as ones that frequently appear in science and technology debates, neither of them appear particularly frequently in our dataset. This is unfortunate, since putting science in a broader and societal perspective, makes information more meaningful to the public and can guide them in discussions about science (Reincke et al., 2020). One methodological explanation for our finding that the social progress frame and economic development/competitiveness frame were relatively uncommon in our corpus, is that we applied rather strict guidelines in our codebook. Only explicit references to social progress or economic development/competitiveness were coded, which may have worked as a limiting factor in identifying these frames. Future research might therefore want to consider taking a somewhat more lenient approach and formulate a broader identification criterion to capture these frames.

In addition, benefits of quantum technology were mentioned in over six times more talks than risks. Only 4% of the talks provided a balanced view (including both a benefit and risk frame), which Cobb (2005) showed eliminates framing effects in the case of nanotechnology. The predominant evaluation of quantum technology in TEDx talks is thus a positive one. This is similar to nanotechnology (a field closely related to quantum technology) as news media coverage mainly framed nanotechnology in terms of benefits (Gurr & Metag, 2022). Due to the fact that risks are hardly mentioned in TEDx talks, we conclude that a narrow public good frame is present in that sense.

Our results showed that, although not statistically substantiated, these four frames (i.e. the economic development/competitiveness, social progress, benefit and risk frame) were used more often by experts than non-experts. Perhaps, this is an indication that experts do try to share input around quantum science and technology in a meaningful way (Reincke et al., 2020), although the fact that experts hardly mention risks of quantum technology supports Roberson et al.'s (2021) advice (i.e. that experts should reflect wider on how quantum research could benefit and harm society). From our analysis it remains unclear what the input of non-experts is. Given that the majority of speakers in our dataset are non-experts who are likely not actively involved in the quantum science and technology field, future research should characterize their input and analyse if it contributes in a meaningful way to sharing input around quantum science and technology.

2.5.4 Quantum science applications: a focus on quantum computing

Finally, the quantum computer/simulator was the most often mentioned quantum science application. Both experts as well as non-experts focused on quantum computing. Based on these findings, we concur with Roberson et al.'s (2021) recommendation to experts to pay attention to a wider range of quantum 2.0 technologies.

Of the three quantum 2.0 technologies identified, quantum sensors were mentioned the least, even though specific quantum sensors could very well have societal implications before quantum computing (European Quantum Flagship, 2020). The complaint by one of the quantum physicists interviewed by Roberson et al. (2021) who said that there is a focus on quantum computing is consistent with our results.

2.6 Conclusion

We performed a content analysis on 501 TEDx talks that cover quantum science and technology. Findings indicate that only some of the potential issues related to the popular communication of quantum science and technology are common in

TEDx talks, and that there are differences in experts' and non-experts' references to these issues. For instance, the spooky and enigmatic frame is apparent but not dominant, and an explanation of underlying quantum phenomena is relatively often accompanied by the mention of quantum 2.0 technology. This implies that some of the concerns among researchers about potential issues that may hinder public engagement with quantum technology are not as prevalent in popular communication as assumed; at least not in TEDx talks.

It should be noted that the Global South was underrepresented in our study: almost 80% of the TEDx talks in our dataset are from Europe and North America. To gain a more global perspective, additional research should analyse TEDx talks in languages other than English. Moreover, additional research is needed to make empirically based claims about both the choices speakers make when communicating about quantum science and technology and the effects of different frames on general audiences. In this undertaking, such future studies should also take the origins of the actual publics that the TEDx talks reach into consideration. Future research should reveal whether the patterns we have seen in TEDx talks also occur in other forms of popular communication about quantum science and technology, such as popular science books, documentaries and games. The findings in this study can serve as a starting point for such studies.

Finally, we already encourage quantum experts to reflect on these findings, especially in giving a more balanced view on the impact of quantum technology when talking to a broader audience, to enhance an open societal discussion on the future impact of quantum technology.

CHAPTER 3

Quantum in the Media: A Content Analysis of Dutch Newspapers

This chapter is based on: Meinsma, A. L., Rothe, T., Reijnierse, W. G., Smeets, I., & Cramer, J. (2025). Quantum in the Media: A Content Analysis of Dutch Newspapers. *Science Communication*, *0*(0). https://doi.org/10.1177/10755470251318300

Abstract

Quantum technology is expected to have an impact on society. Earlier literature suggests that certain frames may either create barriers or facilitate effective science communication. We studied 385 Dutch newspaper articles for the use of these frames. Newspapers commonly explained quantum phenomena when mentioning quantum technology. They also regularly presented quantum technology as beneficial and enigmatic, often in prominent positions of the articles. The frames on economic development/competitiveness, mystical viewpoint, social progress, and risks were less common. Although these barriers are only potential barriers, we encourage journalists to weigh them when communicating about quantum technology.

3.1 Introduction

In October 2019, Google claimed to have reached a milestone. They argued they had built a so-called quantum computer that could perform a task in 200 seconds, when - according to them - the world's best supercomputer would take around 10,000 years to complete the task (Arute et al., 2019). News media worldwide paid attention to Google's achievement, including Dutch newspapers.

Het Parool, for instance, wrote about possible benefits (Van Unen, 2019)[1]:

> According to Google, the possibilities are endless in the long term. Think of connecting the data points from which weather forecasts are drawn up at lightning speed, or predicting changes in climate.

De Telegraaf, on the contrary, ended their article with concern ('Geheimschrift', 2019):

> It [i.e. the quantum computer] offers many possibilities, but also potential problems. The encryption, which secures our e-mail traffic, can be cracked in the blink of an eye. And if I were the secret service, I would already start thinking of an alternative to my secret code.

The media coverage of Google's achievement illustrates that quantum technologies, which include quantum computers, are communicated in different ways. Quantum technologies are emergent technologies that use quantum physics principles, which describe the behavior of particles at very small scales. These new technologies are categorized into the domains of quantum computing and simulation, quantum communication, and quantum sensing and metrology (Stichting Quantumdelta NL, 2020). There are several applications envisioned for quantum technologies, for example, quantum computers for drug discovery (Outeiral et al., 2021), a quantum internet for secure communication (Wehner et al., 2018), and quantum sensors for monitoring underground infrastructure (Stray et al., 2022).

Most of these technologies are still in their infancy, but it is expected that once they mature, they will start to impact society at large (European Quantum Flagship, 2020; Stichting Quantumdelta NL, 2020; Vermaas et al., 2019, 2022). Therefore, it is important already at this early stage to consider public engagement with quantum technology, which means dialogue and deliberation with the public early in the technology's development (see "upstream engagement"; Mooney, 2010; Priest, 2010). One of the reasons for this is to ensure that the technology is built in a socially robust way (Roberson et al., 2021).

[1] The quotes have been translated from Dutch.

The different ways in which quantum technology is communicated to newspaper readers can impact public engagement in diverging ways. For one, *Het Parool*'s statement that quantum computing can accurately forecast the weather has been called "really far-fetched" (Ezratty, 2022, p 8). Although it is feared that such hyped-up promises will result in a decline in public trust in scientists (Ezratty, 2022), they may also help by raising awareness and subsequently spark new discussions (Roberson, 2020). The "quantum computing as a threat" narrative, which *De Telegraaf* mentioned, could also affect public engagement. According to Seskir et al. (2023), this narrative, without presenting a realistic timeline or information on how organizations are already actively working on dealing with the threat, could place time restrictions on potential public engagement and deliberation activities.

As quantum technologies are expected to impact society in the future, there is a role for science communicators and journalists in the process of public engagement with quantum technology. In this article, we quantitatively examine how quantum science and technology are communicated in Dutch newspapers. The theoretical concepts on which our study is based are covered in detail in the next section.

3.2 Theory

Most members of the public become acquainted with scientific information through science-news articles published in (online) media (Schäfer, 2017). In the current online era, despite the emergence of new media platforms such as blogs, social networking sites, and video sharing sites, traditional news media continue to play an important role (Weimann & Brosius, 2017). In the Netherlands, for instance, both online and print newspapers are a frequently used source through which citizens interact with information about science and technology (European Commission, Directorate-General for Communication, 2021; Rathenau Instituut, 2021).

As newspapers and other forms of traditional news media emphasize certain news, for instance through the amount of coverage, they can impact what the public considers to be important topics (Lou et al., 2019). This is known as first-level agenda setting (McCombs & Shaw, 1972). In addition to this first level, agenda setting theory also includes a second level (Scheufele & Tewksbury, 2007; Weaver, 2007; Weimann & Brosius, 2017). While the first level is concerned with *which* topics are discussed in the media, the second level is concerned with *how* the media communicate about those topics (Weaver, 2007). For instance, when discussing a given topic, media outlets can focus on frames such as the benefits or risks involved in the issue at hand (Chuan et al., 2019; Lewenstein et al., 2005; Strekalova, 2015; Veltri, 2013), which can subsequently influence people's attitudes toward the issue

(Achterberg, 2014; Cobb, 2005; Druckman & Bolsen, 2011).

The influence of news media is particularly important in the case of emergent technologies (Scherrer, 2023; Scheufele & Lewenstein, 2005), as this is likely the first exposure people have to such a technology. News media coverage for emergent technologies usually seems to follow a typical attention cycle of a bell-shaped curve of salience: it starts off with a growing amount of coverage followed by a decline (Lewenstein et al., 2005; Nisbet et al., 2003; Veltri, 2013). Previous content analyses of emergent technologies, such as nanotechnology (Lewenstein et al., 2005; Strekalova, 2015), artificial intelligence (AI) (Chuan et al., 2019), and stem cells (Nisbet et al., 2003), show that the news media in general paint a positive picture when reporting on these technologies. The emphasis is, for instance, on frames such as business opportunities and social progress. At the same time, attention is also paid to the risks of the technologies. For example, a content analysis of nanotechnology in the Spanish news media showed that controversies were reported early on (Veltri, 2013). A content analysis of AI in the U.S. news media found that risks were covered less but in more depth than the benefits (Chuan et al., 2019).

An important emergent technology currently under development is quantum technology. It holds the potential to impact society at large once it arrives (Stichting Quantumdelta NL, 2020; Wehner et al., 2018). As with any new technology, quantum technology poses both benefits and risks for society. For example, quantum computers have the potential to design new types of materials and molecules that could save or extend lives through drug discovery (Outeiral et al., 2021), but they can also enable new forms of modern warfare that could fall in the hands of terrorist groups (Vermaas et al., 2019).

Because of the expected impact of quantum technology, it is important to establish good connections between quantum and society. This means engaging the public early in the technology's development and building up trust in society (Mooney, 2010). However, literature warns of barriers to effective public communication about quantum, which could hinder public engagement (Seskir et al., 2023; Vermaas, 2017) and public trust (Grinbaum, 2017). At the same time, there is also a plea for sufficient attention to reflect on the impact of quantum technology on society (Roberson et al., 2021).

In terms of barriers to effective public communication about quantum, Vermaas (2017), for instance, argues that quantum is often communicated as enigmatic. He argues that this could hinder public understanding of quantum technology and subsequent engagement in societal dialogues to explore the implications of quantum technology on society. Furthermore, according to Seskir et al. (2023), describing quantum technology in terms of having to win a race poses a barrier to participatory efforts with quantum technology between different stakeholder groups. In a military context, for instance, it can lead to research having to be kept secret for certain groups. Third, Grinbaum (2017) states that popular media do not explain underlying quantum phenomena when mentioning quantum technology, which he argues could influence the public's trust in quantum technology. Finally, mystical viewpoints of quantum, often found in popular scientific talks (Chapter 2), present a pseudoscientific, inaccurate image of quantum. As such, this potential barrier can result in misconceptions about its applications (Bondani et al., 2024).

In contrast, Roberson et al. (2021) advocated for focusing on frames that promote effective public communication about quantum. This includes highlighting ways in which quantum technology can impact society for the better while its risks are minimized. The authors encourage a reflection on the ways in which quantum technology might improve or solve problems in people's lives (i.e., the social progress frame) and this reflection should entail both the risks and the benefits of quantum technology, thereby providing a balanced perspective.[2]

In Chapter 2, we studied the prevalence of the different quantum-related frames described above in a content analysis of 501 TEDx talks. Results of our analysis showed that while the spooky and enigmatic frame occurred in about a quarter of the talks, the quantum race frame and the mystical viewpoint frame were hardly present. In addition, and contrary to what had been suggested in the literature, relatively many TEDx talks contained quantum phenomenon explanations. Regarding the balanced perspective, benefits greatly outnumbered the risks, while reference to social progress was scarce. Only some of the concerns from literature were thus present in TEDx talks, and overall, quantum was portrayed in a positive way.

While TEDx talks reach a rather specific audience (their local audiences and web users; Mattiello, 2019), most members of the general audience will likely learn about quantum through (online) news media. As agenda setting predicts that what and how is being talked about in these media may affect people's perceptions of emergent technologies, it is important to examine if (first-level agenda setting) and how (second-level agenda setting) quantum technology is communicated in news outlets. The Dutch scientific community is heavily involved in quantum technology (Stichting Quantumdelta NL, 2020), and the societal connection is explicitly mentioned in its National Agenda Quantum Technology. In this study,

[2]Note that the balanced perspective advocated by Roberson et al. (2021) differs from the issue of "balance as bias" or "false balance," which deals with the bias that arises from balanced science reporting, when, for example, voices that contradict scientific findings receive as much attention as the scientific findings themselves (Boykoff & Boykoff, 2004).

we, therefore, investigate to what extent and in which ways quantum technology is communicated in Dutch newspaper articles. Our research questions are as follows:

Research Question 1: (a) Which attention cycle do Dutch national newspapers follow in relation to quantum technology and (b) which of the quantum domains (computing and simulation, communication, sensing and metrology) receive most attention?

Research Question 2: How often are the following frames present in Dutch national newspaper articles about quantum science and technology?

(a) spooky and enigmatic

(b) economic development/competitiveness

(c) explaining fundamental quantum phenomena when mentioning quantum technology

(d) mystical viewpoint

(e) social progress

(f) benefits

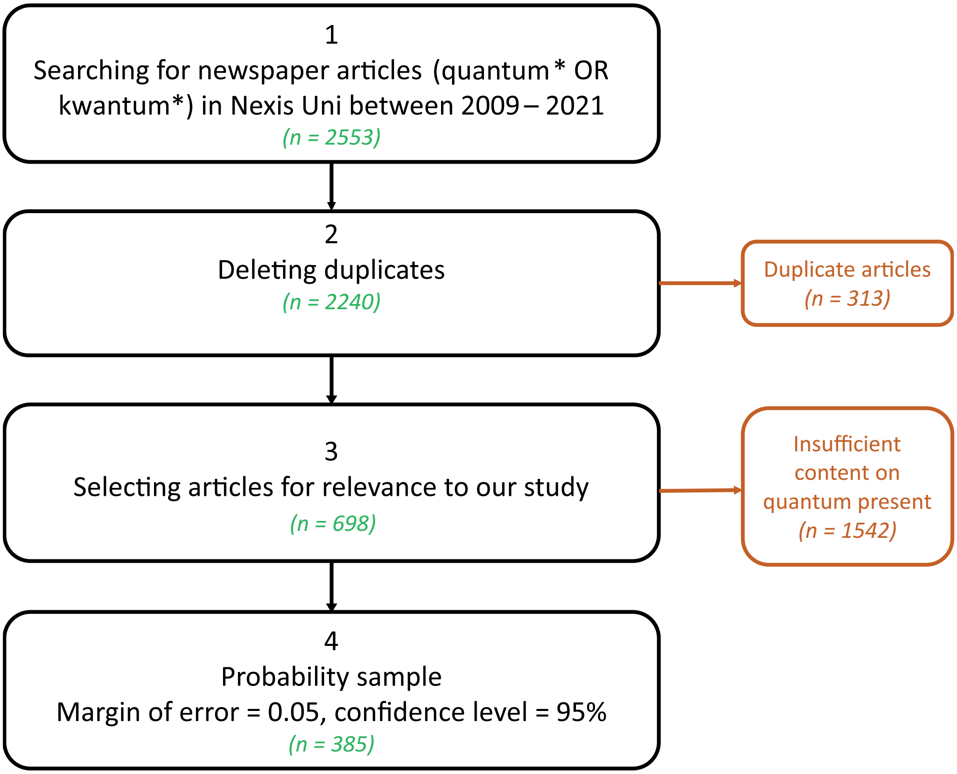
(g) risks

Moreover, news articles have a specific structure, such that the most important information is shared first, while the remaining text presents less important information (Angler, 2017). This implies that frames positioned in the beginning of news articles (e.g., in the head) are the most prominent. Magusin (2017) highlights three features of heads that make them worth studying. First of all, readers tend to read heads more often than the full article itself. Second, the information in the head guides readers toward the facts presented in the article. And finally, heads rely on cultural knowledge that is believed to be widespread in society, and therefore, they may influence the dominant discourse more than the rest of the article. We argue that in addition to the head, the subhead and lead also contain important information (Angler, 2017), and therefore, we ask

Research Question 3: Which frames do journalists most often place in a prominent location?

Figure 3.1

Data collection method.



3.3 Methods

3.3.1 Sample collection

To answer the research questions, we collected a sample of Dutch newspaper articles with quantum science and technology content. Our data collection method is shown in Figure 3.1. We used the search string "quantum* OR kwantum*" in the Nexis Uni database ('LexisNexis. Nexis Uni', n.d.) and set the search window from January 1, 2009 (the year in which the first quantum computer was unveiled Hanneke et al., 2010) to December 31, 2021. Articles written by the six major Dutch newspapers as listed in the rankings of Nationaal Onderzoek Multimedia (NOM) Dashboard 2022-I were included, namely *Algemeen Dagblad*, *De Telegraaf*, *De Volkskrant*, *NRC*, *Trouw*, and *Het Parool*. The search returned a total of 2,553 articles.

In the second step, duplicate articles were deleted via a hybrid automatic-manual process. Details of this process can be found in Section A2.1 in the Appendix and in the referenced source code.[3] It resulted in a total of 2,240 unique articles. Afterward, we selected the articles with sufficient quantum science and technology content for our study. The reasons for discarding an article are included in Table A7 in the Appendix. The primary reason (n = 599) for excluding an article was due to using the search string in a company or product name, for example, references to the Dutch company “Kwantum” or the James Bond film “Quantum of Solace.” The two first authors of this article checked the article selection on a 20% random sample of the data set, which resulted in an acceptable level of agreement (α = 0.830, 92.4%; Krippendorff, 2004). In total, we discarded 1,542 articles which left us with a data set of 698 articles. The metadata of all these articles were obtained through Nexis Uni (‘LexisNexis. Nexis Uni’, n.d.), which included the newspaper brand, the section in which the article was published, the date of publication, the article headline, the name of the author, and the word count of the article.

Based on formulas for standard error and confidence intervals (Neuendorf, 2017), we drew a random sample of 385 articles for our analysis. We opted for a simple random sample due to limited coding resources, and sampling theory suggests that coding the entire data set is unnecessary as we can be 95% confident that the true population percentage is within 5% of the sample percentage. Descriptives of the sample are shown in Table A8 in the Appendix.

3.3.2 Codebook

The codebook was based on the codebook from Chapter 2 (see the Appendix A1.5).

We coded the barriers to effective communication of quantum science and/or technology. If a frame was found, the sentence that reveals the frame was copied into the coding sheet. The spooky and enigmatic frame was identified when “quantum” was associated with “spooky” or “enigmatic” or a synonym of those terms. Second, the economic development/competitiveness frame was found when a news article made reference to the effect that quantum science and technology can have on the economy, and/or when the article highlights the competitive side on a local, national, or global level (see Nisbet, 2009). Third, we identified the presence of an explanation of three types of fundamental quantum phenomena: superposition, entanglement, and contextuality in articles that make reference to quantum technology (i.e., articles with a quantum technology indicator). An explanation of superposition includes that a particle can be in multiple states at the same time; of entanglement that two particles share a quantum state, meaning

[3] Code repo available at https://github.com/t-rothe/quantum-in-Dutch-newspapers.

that it does not make sense to discuss those particles as separate entities anymore; and finally, contextuality is considered a harder concept (see G. Jaeger, 2019), which we operationalized as that performing a measurement irreversibly affects a quantum state. Finally, the mystical viewpoint was identified when an article included ideas that do not adhere to established scientific paradigms of quantum, such as connections to spirituality, religion, and consciousness.

In addition, we coded the frames referring to a balanced perspective on quantum science and/or technology. The social progress frame was present when an article emphasized how quantum science and technology can solve problems or improve people's lives (see Nisbet, 2009). The benefit frame was identified when either a positive evaluation of quantum science and technology was given, quantum science and technology was said to have advantages over something else (e.g., it was attributed to being faster, safer, and better), or when a specific reference was made to how quantum science and technology will benefit a particular field. Note that social progress is inherently a benefit, and therefore, the benefit frame was automatically identified when the social progress frame appeared in the article. The risk frame appeared when concerns about quantum science and technology were highlighted.

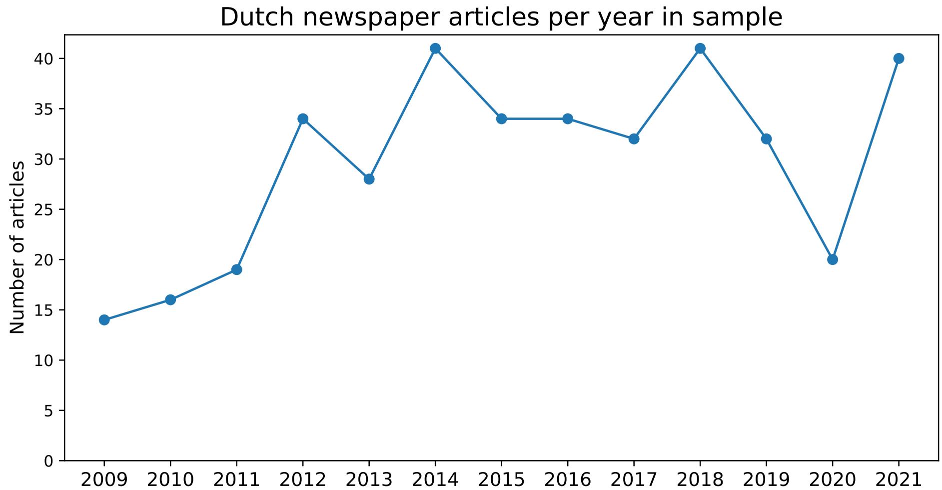
Finally, frames that were placed in the head, subhead, or lead were coded as prominent. We only included news reports and features in this part of the analysis, as these are the articles that typically have a structure with the most important information first, followed by less important information (Angler, 2017).

3.3.3 Coding procedure and reliability

To ensure reliable results, the first two authors conducted three independent coding rounds and discussed similarities and differences in their application of the codebook extensively. The first coding round was a pilot based on 36 articles from 2022. The second round involved drawing a random sample of n = 267 articles with n = 54 articles (20%) for intercoder reliability. Overall, the codebook was reliably applied. Only for certain codes, low occurrences affected reliability, as a slight difference in interpretation between the first and second coders was already detrimental for α. The coders, therefore, extensively discussed the differences and reached a consensus in all cases. With the discussion in mind, one of the coders proceeded with coding the entire sample of 267 articles. Because the coding process went smoother than anticipated, time allowed us to extend our initial sample of 267 articles to 385 articles of which an additional 24 articles were randomly selected for intercoder reliability testing (totaling n = 78 articles, 20% of 385 articles). As Table

Figure 3.2

Frequency of articles by year of publication (n = 385).



A10 in the Appendix shows this procedure ensured overall the reliable application of the codebook and for any remaining disagreements, a consensus was reached between the two coders. The primary coder then proceeded to code the rest of the sample. The details of the analysis plan can be found in Appendix A2.5.

3.4 Results

3.4.1 Amount of coverage

Of the 385 articles in our sample, most articles were published in 2014 and 2018 (in both years: $n = 41$, 10.6%), and the least in 2009 ($n = 14$, 3.6%). As can be seen in Figure 3.2, there are spikes in coverage. Figure A4 in the Appendix shows that the curve of the total number of articles in the complete data set (N = 698 articles) resembles the curve in Figure 2. For an overview of the distribution of articles per year per newspaper in our sample, please see Figure A5 in the Appendix.

Quantum science and/or technology was the main focus in a little less than half of the articles ($n = 170$, 44.2%). The topic of quantum computing and simulation occurred most frequent ($n = 153$, 39.7%), followed by quantum communication ($n = 33$, 8.6%) and only two articles mentioned quantum sensing and metrology (0.5%).

Table 3.1

Frequency table of the newspaper articles comparing the predefined set of frames.

Frame	Total number of articles	%	95% CI
Spooky and enigmatic	93	24.2	[0.199, 0.284]
Economic development / competitiveness	33	8.6	[0.058, 0.114]
quantum phenomenon explanations for articles with quantum technology indicator (n = 178)	90	50.6	[0.432, 0.579]
Mystical viewpoint	10	2.9	[0.013, 0.047][a]
Social progress	13	3.4	[0.018, 0.057][a]
Benefit	128	33.2	[0.285, 0.380]
Risk	21	5.5	[0.032, 0.077]

Note. Multiple frames can occur in one article. [a]indicates the exact Clopper–Pearson confidence interval was calculated.

3.4.2 Frames

Table 3.1 shows the prevalence of the frames that we analyzed. Below, we describe these findings in more detail and provide illustrative examples from our data set.

First of all, the spooky and enigmatic frame appeared in 24.2% of the articles in our sample (n = 93). An example is: ‘The theory behind quantum mechanics is bizarre and counterintuitive. [. . .] There is nothing weirder than quantum mechanics’ (Schenk, 2018). In this example, the terms “bizarre” and “weird” are indicative of the frame as they are semantically similar to the terms “spooky” and “enigmatic.”

Second, the economic development/competitiveness frame appeared in 8.6% of the articles in our sample (n = 33). An example is ‘NSA fears European lead in race for “qubits”’ (Hond, 2014), where competitiveness is highlighted through the word “race.”

Third, to establish whether articles include an explanation of a quantum phenomenon when referring to quantum technology, we analyzed the articles with a quantum technology indicator (n = 178) for including an explanation on superposition, entanglement, and/or contextuality. Results show that 50.6% of the articles with a quantum technology indicator (n = 90) explained at least one of these three phenomena. Out of the three phenomena, superposition is explained most often (see Figure A6 in the Appendix). An example of a quantum phenomenon explanation is as follows:

> If you apply the elusive properties of quantum physics to classical bits, you take the step to the qubit: an information carrier that can be not only zero or one, but also zero and one at the same time, something that physicists call superposition (Hal, 2017).

The mystical viewpoint was found in 10 articles (2.9%). An example appeared in an interview with a theologist, who pleads for connection and solidarity (Huttinga, 2017):

> I find it comforting and telling that quantum physics shows us the same thing: everything is completely intertwined and connected—already at the level of the electron. In the universe, everything is mysteriously connected to everything in every possible way. It is up to us to tune into that.

In only 13 articles (3.4%), reference was made to the fact that quantum would mean something *good* for society and should be developed and deployed in such a way. An example of the social progress frame is as follows: 'According to her, quantum technology is going to revolutionize society. It can provide solutions to global issues in climate, energy, health care, and security' (Van onze correspondent, 2016). The example focuses on quantum technology as a solution to major problems that our society currently faces.

To examine the balanced perspective of quantum technology, we quantified the occurrence of the benefit frame and the risk frame. First of all, the benefit frame appeared in 33.2% of the articles in our sample ($n = 128$). An example is as follows (Van Wayenburg, 2014):

> The promises are great: with control of quantum information you could build quantum computers that calculate faster than all current computers, because they can analyse many billions of variants of the problem at the same time. Quantum information also offers the possibility to transmit information in an non-eavesdropping manner. And then there are probably even more applications that have not yet been thought of.

By stating that "the promises are great," the author gives a positive evaluation of quantum computers. In addition, by using the word "faster" for comparing quantum computers to current computers, the author emphasizes an advantage of quantum computers.

Finally, the risk frame appeared in only 5.5% of the articles in our sample (n = 21). An example is as follows (Brugh, 2016):

> Imagine that everything you email, that you bank online, that you store on your computer, is no longer secure. [. . .] Peter Schwabe (35), cryptographer at Radboud University Nijmegen, is seriously concerned about that scenario. Because with the imminent arrival of quantum computers, which promise unprecedented computing power, this becomes a real danger.

The phrases "seriously concerned" and "a real danger" in relation to the arrival of quantum computers indicate risk. Furthermore, this example mentions a specific field that is being impacted: the digital security/privacy field. To gain more insight into these specific fields that are mentioned to be benefited or harmed by quantum technology, we carried out an additional analysis (see Figure A7 in the Appendix). This showed that the digital security and privacy field were most often mentioned to be impacted by quantum science and technology, both in terms of causing benefits and causing risks to the field.

Table A12 in the Appendix shows the number of times each frame was placed in a prominent location in news reports or features, and its percentage compared with the total number of prominent frames. The benefit frame was most often placed prominently (25×), followed by the spooky and enigmatic frame (15×). In addition, when comparing the number of times a frame appeared in a prominent location with its total occurrences, we found that frames were typically placed prominently in about a quarter of the news reports and features, with percentages ranging from 20% (mystical viewpoint) to 30% (risk), except for quantum phenomenon explanations (15.5%) and social progress (8.3%).

3.5 Discussion

This study examined how quantum physics and technology were described in Dutch newspapers during the period 2009 to 2021. We quantified the occurrence of frames relevant to the setting of quantum science and technology.

3.5.1 First-level agenda setting: how often is quantum technology written about?

Both in the fully coded sample (385 articles) and in the total data set of 698 articles with quantum science and technology content, we find that the typical bell-shaped curve of salience for emergent technology is not (yet) visible (such as for nanotechnology in the American and Spanish news; Lewenstein et al., 2005; Veltri, 2013). Overall, we see an upward trend interrupted by several dips, including one in 2020 that may be related to COVID-19. As quantum technology is in an early stage of development, it is possible that we are currently at the start of the bell-shaped curve of salience.

Between 2009 and 2021, the six major Dutch newspapers wrote an average of around 50 articles per year with content about quantum science and technology. This number seems relatively small compared with the number of research outcomes in the Dutch media in general (Hijmans et al., 2003) and compared with the prevalence of other physics disciplines (Kristensen et al., 2021). It may thus be that the public has not yet been largely exposed to quantum science and technology and may not know much about it yet.

3.5.2 Second-level agenda setting: how is quantum science and technology written about?

We identified how quantum science and technology are described in Dutch newspaper articles, focusing on both potential barriers to, and potential facilitators of, effective science communication suggested in the literature. Contrary to claims from the literature, the economic development/competitiveness frame (Seskir et al., 2023) and mystical viewpoint (Bondani et al., 2024) were relatively uncommon (8.6% and 2.9%, respectively). This suggests that these potential barriers might not be very salient in the minds of Dutch newspaper readers and possibly less influential for the way people think about quantum science and technology. By contrast, quantum phenomenon explanations (Grinbaum, 2017) were relatively frequent (50.6%), indicating that this barrier (i.e., lack of explanation) is not overly prominent in media coverage of quantum.

At the same time, however, the frequency of other frames aligns with concerns voiced in the literature. The spooky and enigmatic frame (Vermaas, 2017) appeared relatively often (24.2%), whereas the social progress frame (Roberson et al., 2021) was hardly present (3.4%). Furthermore, the frequency of the benefit frame (33.2%) largely exceeded that of the risk frame (5.5%), creating an unbalanced perspective (Roberson et al., 2021) on quantum in Dutch newspapers. In addition, the benefit frame and the spooky and enigmatic frame were often placed in prominent locations within news reports and features, potentially making them more influential than other frames. We, therefore, encourage journalists and science communicators to carefully consider the use and positioning of these frames in their public communication about quantum.

In comparing quantum technology coverage to that of other emerging technologies, it is surprising that the focus on economic benefits (Chuan et al., 2019; Lewenstein et al., 2005; Nisbet et al., 2003) and social progress (Chuan et al., 2019; Nisbet, 2009) is less clear. However, the tendency of news media to paint a positive picture while rarely mentioning the risks of quantum technology is consistent with other emergent technologies (Chuan et al., 2019; Lewenstein et al., 2005; Nisbet et al., 2003; Strekalova, 2015; Veltri, 2013). We know from previous research that a positive focus in news media can have a positive effect on the acceptance of emergent technologies (Scherrer, 2023; Scheufele & Lewenstein, 2005). Future research should investigate whether this is also the case in this context.

3.5.3 Limitations

A limitation of our study is that we used a predefined set of frames to code the data, which may overlook other interesting frames that a bottom-up approach could reveal. In addition, only a small number of authors contributed significantly to the coverage of quantum science and technology in Dutch newspaper articles, suggesting possible self-reinforcing effects as journalists look at each other's articles or previous work. Since our study focused on a single country, the Netherlands, this may limit the generalizability of our findings. We, therefore, encourage replication in different contexts for the external validity of the study. Finally, although the concept is more nuanced, we operationalized contextuality as the idea that a measurement irreversibly affects a quantum state. We have limited our codings to only address this aspect of a measurement because of the concept's complexity. Further qualitative research could examine which quantum phenomena are all described and how deeply they are discussed in popular communication.

3.5.4 Practical implications

News articles may influence perceptions and subsequent attitudes toward quantum technology. Therefore, we encourage journalists and science communicators to already consider the potential barriers and potential facilitators to effective science communication in literature. This way, communication about quantum might jump from a state of superposition - where it is effective and ineffective at the same time - to one of effectiveness.

CHAPTER 4

The Effect of Frames on Engagement with Quantum Technology

This chapter is based on: Meinsma, A. L., Albers, C. J., Vermaas, P., Smeets, I., & Cramer, J. (2024). The effect of frames on engagement with quantum technology. *Manuscript Under Review*.

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.

[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.

CHAPTER 5

Like a Coin Spinning in the Air: The Effect of (Non-) Metaphorical Explanations on Comprehension and Attitudes Towards Quantum Technology

This chapter is based on: Meinsma, A. L., Reijnierse, W. G., & Cramer, J. (2025). Like a coin spinning in the air: The effect of (non-) metaphorical explanations on comprehension and attitudes towards quantum technology. *Manuscript Under Review*.

Abstract

The complexity of the science underlying quantum technology may pose a barrier to its democratization. This study investigated whether metaphors improve comprehension of, and shape attitudes toward, quantum technology. In an online experiment (*n* = 1,167 participants representative of the Dutch population), participants read a news article that included a metaphorical, non-metaphorical, or no explanation of a quantum phenomenon. Both explanation types reduced perceived comprehension of the news article compared to the control group, but increased actual comprehension of the quantum phenomenon. No direct effects were found on affect-based or cognition-based attitudes. Mediation analyses revealed a very small negative indirect effect of explanations on attitudes, through lower perceived comprehension, and a very small positive indirect effect of explanations on attitudes via increased actual comprehension – though the latter was counteracted by a negative direct effect. As metaphors offered no additional benefit over non-metaphorical

explanations, the findings suggest they do not provide a communicative advantage for enhancing understanding or shaping attitudes in this context.

5.1 Introduction

Emergent technologies – defined as quickly growing, scientifically-based innovations whose market potential has not yet fully been exploited (Cozzens et al., 2010) - may feel intangible to the general public. Moreover, public awareness of such technologies is typically limited (Cobb & Macoubrie, 2004; Scheufele & Lewenstein, 2005). Public reactions to previous emergent technologies have shown that public resistance can arise (Kurath & Gisler, 2009). This highlights the importance to take early account of how the general public perceives a new technological development (Mooney, 2010). Engaging the public early in a technology's development can help scientists better understand people's concerns, before a conflict arises (Mooney, 2010).

An example of a current emergent technology is quantum technology. Quantum technology encompasses three domains: quantum computing and simulation, quantum communication, and quantum sensing and metrology (Stichting Quantum Delta NL, 2020). This technology holds the promise of significant societal benefits. For instance, quantum technology promises "a new window into the underground" (p 1), thereby reducing the risk of encountering unexpected ground conditions during the construction of vital energy, transportation, and utility infrastructure (Stray et al., 2022). It may also assist in improving computations that are important for the development of new drugs (Outeiral et al., 2021), and promises to enable fundamentally secure communications globally (Wehner et al., 2018). In contrast, quantum technology raises potential concerns and ethical implications, for instance through the question of who gets access and who falls behind (Ten Holter et al., 2022), and through its potential for criminal use (Vermaas et al., 2019). In addition, the science behind quantum technology is counterintuitive to what we experience in our daily lives, which makes it difficult to grasp.

One way that may make the science behind quantum technology easier to understand is through the use of metaphors. A well-known example is Schrödinger's cat[1] (Van de Merbel et al., 2024), which uses the metaphor of a cat in a box - where the cat is both dead and alive at the same time until the box is opened - to describe the quantum phenomenon of particles existing in two states simultaneously. By comparing an abstract quantum phenomenon (the target domain) to a cat in a box (a more concrete source domain), metaphors are used to bridge the gap between

[1]Schrödinger's cat is a thought experiment devised by Erwin Schrödinger (Die gegenwärtige Situation in der Quantenmechanik, E. Schrödinger, 29 Nov, 1935) to illustrate the paradoxes of quantum mechanics under the Copenhagen interpretation, but it is now more commonly used as a metaphor to explain quantum mechanics in popular culture (Wikipedia contributors, 2025a).

complex quantum phenomena and everyday experiences.

Metaphors are for instance used in newspaper articles about quantum science/technology (Hilkamo & Granqvist, 2022; Wackers et al., 2025), which are important sources for people to get to know about quantum technology (European Commission, Directorate-General for Communication, 2021; Van de Merbel et al., 2024). However, to our knowledge, little is known about the effects of such metaphors on news media recipients.

In this article, we examined the effects of (non-)metaphorical explanations of counterintuitive quantum phenomena in a news article about quantum technology. Specifically, we studied whether (non-)metaphorical explanations influence people's comprehension and attitudes towards the technology.

5.2 Theory

As science and technology are often abstract, complex and unfamiliar, metaphors may make them more concrete, simpler, and easier to understand (Lakoff & Johnson, 1980). According to Lakoff and Johnson (1980) metaphors are a mapping between different domains (note that based on this definition, analogies and similes also fall under the term 'metaphor', which we have therefore also referred to as metaphor throughout this article). Metaphors in communication of science and technology towards a general public generally function to explain a scientific concept in terms of a more familiar one (Beger & Smith, 2020; Smedinga et al., 2023). In this way, metaphors could be helpful in making the complex field of quantum technology more accessible.

5.2.1 Incomprehensible quantum science could limit public engagement

There is a call for making quantum technology more accessible and comprehensible to a general public (Coenen et al., 2022) and engage them early on in its development process (Roberson et al., 2021). One of the reasons for this is that involving a wider group of people in envisioning the impact of quantum technology fits a more democratic process, in which citizens can express their opinions and concerns about developments that may affect them (Van Dam et al., 2020). Moreover, engaging the public in quantum technology may contribute to more public support and less resistance towards it, with previous emergent technologies such as nuclear energy and biotechnology having to deal with public resistance (Druckman & Bolsen, 2011; Kurath & Gisler, 2009).

However, the science that underlies quantum technology is complex, which could draw a barrier for public engagement. This may be reinforced by experts who emphasize this complexity in their outreach. Using Richard Feynman's well-known remark "I think I can safely say that nobody understands quantum mechanics" (Feynman, 1967, p 129), experts tend to focus on quantum mechanics as something that is incomprehensible (Seskir et al., 2023). This focus could be bad for the democratization of quantum technology, as it could hinder comprehension and engagement in discussions on its impact on society (Coenen et al., 2022; Seskir et al., 2023). Research on public engagement with quantum technology found that respondents in the Netherlands felt they had little influence over the development of quantum technology (Van de Merbel et al., 2024), and in the UK participants felt quantum technology was complicated and for experts only (Busby et al., 2017).

An open question in communication about quantum technology is what types of information allow for a good connection between quantum and society. As metaphors may influence comprehension (section 5.2.2) and attitudes (section 5.2.3), together with the fact that comprehension may influence attitudes (section 5.2.4), metaphors are an important tool to study.

5.2.2 Effect of metaphor on comprehension

One of the functions of metaphors in science is to make scientific topics easier to understand (Beger & Smith, 2020). However, metaphors have been found to create differences between what someone feels they have understood from a text (perceived comprehension) and what they actually understood (actual comprehension, see A. J. Jaeger & Wiley, 2015; Wiley et al., 2018). Specifically, metaphors can cause people to believe that their understanding of a text is higher than it actually is (i.e., illusion of comprehension, A. J. Jaeger & Wiley, 2015; Wiley et al., 2018). A. J. Jaeger and Wiley (2015), for instance, found that students who read a text about the greenhouse effect were generally overconfident in their understanding, but those in the metaphor-enhanced text condition were even more overconfident than the ones in the control group.

When looking specifically at actual comprehension, metaphors may not necessarily improve it. While in the field of education some studies have reported positive effects, with metaphor-enhanced texts supporting recall (Glynn & Takahashi, 1998) and reasoning (Yanowitz, 2001), other studies found no significant effects with the metaphor-enhanced texts resulting in similar comprehension results as control texts (Alexander & Kulikowich, 1991; Braasch & Goldman, 2010). Metaphors can even have detrimental effects on comprehension when learners map features between source and target domains that cannot be mapped, leading to misconceptions (Zook & Maier, 1994).

While metaphors in scientific educational texts have been well-studied, it remains unclear whether - and how - metaphors influence comprehension in science communication. A study in environmental communication by Reijnierse et al. (2025) showed that sustainability metaphors increased people's perceived comprehension of the text: people in the metaphor condition rated their comprehension significantly higher than those in the control group. However, there was no significant difference between the groups in terms of actual comprehension.

5.2.3 Effect of metaphor on attitude

Meta-analyses by O'Keefe and Hoeken (2021), Sopory and Dillard (2002) and Van Stee (2018) found that metaphors have a small positive effect on attitudes compared to literal messages. Metaphors with a familiar target domain furthermore led to more positive attitudes than those with an unfamiliar target domain, likely because the latter requires too much cognitive effort to process (O'Keefe & Hoeken, 2021; Sopory & Dillard, 2002; Van Stee, 2018). The effect of metaphors on attitudes, however, appear to be variable, as a next, individual study may also find a negative effect size instead of a positive one (O'Keefe & Hoeken, 2021).

While these meta-analyses included studies from contexts such as advertising, politics, environmental issues and health, none of them included studies focusing on new technology. To our knowledge, the effect of metaphor on attitudes towards new technology remains unclear. Prior research has shown that even when information is very limited, people can form attitudes towards new technology instantly (Druckman & Bolsen, 2011; Van Giesen et al., 2015). These attitudes may be based more on affect – i.e., emotions and feelings towards the technology, or cognition – i.e., thoughts and beliefs towards the technology. For unfamiliar technologies, people tend to rely more on affect, whereas this changes over time when cognition starts to play a bigger role (van Giesen et al., 2018). Examining both affective and cognitive responses to an emergent technology can therefore form a good image of people's attitudes.

5.2.4 Effect of comprehension on attitude

Research suggests that comprehension is important in attitude formation and change (Wyer Jr & Shrum, 2015). For example, comprehension of information that creates a visual image in one's mind, as well as information that is presented in the form of a story, can have a stronger effect on one's attitude. Even when the features that make a text more vivid and therefore easier to remember are completely irrelevant to the attitude in question - as in determining one's guilt in a court case after a delay in viewing the evidence - they can still influence attitude formation (Wyer Jr & Shrum, 2015).

For emergent technology specifically, people's beliefs of having enough information to form a judgment may influence their attitudes more than what they actually know (Akin et al., 2021). In an online survey in the US, Akin et al. (2021) found that people's perceptions of their own knowledge significantly predicted their positive attitudes towards three emergent technologies (nuclear energy, nanotechnology and synthetic biology). In contrast, people's actual knowledge only predicted two of those technologies – for the newest of the three technologies, synthetic biology, actual knowledge did not significantly predict attitudes. This provides reasons to investigate the relationship between comprehension and attitudes in the context of emergent quantum technology.

5.2.5 Metaphors in communication about quantum technology

Metaphor use has already been specifically recommended in public communication about quantum technology (Grinbaum, 2017; Hilkamo & Granqvist, 2022). Grinbaum (2017), for instance, has emphasized from a philosophical viewpoint the importance of effectively explaining counterintuitive quantum phenomena to ensure the public can grasp the basics of what quantum physicists work with daily. Without this comprehension, people's perception of quantum technology may become more negative. To address this, Grinbaum (2017) suggests metaphors to explain the science and at the same time convey the beauty of quantum science. Hilkamo and Granqvist (2022) have also emphasized the importance of metaphors in the quantum technology domain, as they can appeal to emotions.

It is not yet known exactly how metaphors influence comprehension and attitudes in public communication such as news articles about quantum technology. Our research therefore aims to explore whether a (non-)metaphorical explanation of a quantum phenomenon in a news article affect comprehension (both perceived and actual) and shape attitudes (both cognition- and affect-based).

Prior studies worked with metaphor-enhanced texts, where the metaphor was added to the original explanation (see e.g., Alexander & Kulikowich, 1991; Braasch & Goldman, 2010; Glynn & Takahashi, 1998; A. J. Jaeger & Wiley, 2015; Yanowitz, 2001). However, this results in a double explanation of the phenomenon – once non-metaphorically and once metaphorically. Because we are interested in whether a metaphorical explanation in itself provides benefits, we work with three different conditions. Our research questions are as follows (see Figure 5.1 below):

Research Question 1: To what extent does the use of a non-metaphorical quantum phenomenon explanation vs a metaphorical quantum phenomenon explanation vs a control in a news article influence:

(a) perceived comprehension of the news article[2]

(b) actual comprehension of a quantum phenomenon

(c) affect-based attitudes towards quantum technology

(d) cognition-based attitudes towards quantum technology

Research Question 2: To what extent does perceived comprehension of the news article mediate the possible effects of explanation type (non-metaphorical quantum explanation, metaphorical quantum explanation, no explanation) on affect- and cognition-based attitudes?

Research Question 3: To what extent does actual comprehension of the quantum phenomenon mediate the possible effects of explanation type (non-metaphorical quantum explanation, metaphorical quantum explanation, no explanation) on affect- and cognition-based attitudes?

5.3 Methodology

Following our research questions, we performed an online experiment. The study information, design plan, sampling plan, variables and analysis plan were preregistered on the Open Science Framework before the data collection started (https://tinyurl.com/mr3hp4w9). The Ethics Review Committee of the Faculty of Science, Leiden University gave ethical approval to conduct the study (reference number 2023-021). The following section gives an overview of the materials used, the design and procedure, the participants and the variables of the study.

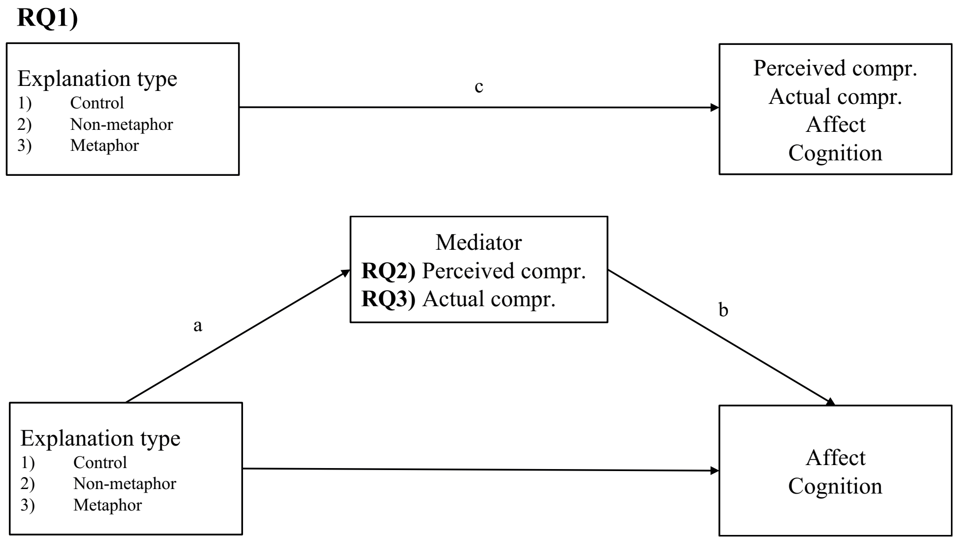
5.3.1 Materials

We designed a newspaper article about a new quantum computer that the European Commission has decided to build in the Netherlands as stimulus material. The article was based on an actual event (see NOS, 2024). The text contained 162 words

[2]Here we deviated from the preregistration, given that we made the call to examine perceived comprehension of the text as a whole, informed by previous studies that measured perceived comprehension at the level of the entire text.

Figure 5.1

Visual representation of the research questions. The top path diagram illustrates RQ1, examining the direct relationships between the variables. The bottom path diagram shows the two mediation models: RQ2 examines perceived comprehension as a mediator, and RQ3 examines actual comprehension as a mediator.



in the control conditions, with an additional paragraph of 73 to 80 words included in the explanation conditions. The text of the news article and different conditions can be found in Appendix A4.1.

We chose to explain the quantum phenomena *superposition* or *entanglement* in the explanation conditions. These phenomena are relevant to study as they underlie quantum technology, are counterintuitive from the perspective of everyday experiences and are often explained to general audiences in popular communication (Chapters 2 and 3). To identify which metaphor for superposition and entanglement were deemed most accurate for communicating with non-experts, we conducted a small study among Dutch-speaking quantum experts.

Expert insights: method

We emailed an online survey to 67 researchers from Dutch universities, who were selected based on their university profiles. Only those working in a field where quantum physics plays a role and with Dutch as a native language could participate. First, we asked participants to provide consent. Then, after indicating that Dutch was (one of) their native language(s) and indicating the quantum-related field in which they worked (based on Fox et al., 2020), participants were randomly assigned to read five metaphors about a quantum phenomenon (superposition or entanglement) that were displayed in a random order. The metaphors were generated by ChatGPT 3.5, as this AI tool is widely used and known for its accessibility and as science communication research encourages investigating the accuracy of AI-generated content (Schäfer, 2023). The precise wordings per metaphor can be found in Table A17 in the Appendix.

After reading each metaphor, participants rated its accuracy and validity on a 7-point Likert scale. They also indicated how likely it would be for them to use a metaphor when talking to a non-quantum expert about superposition or entanglement (7-point scale). Next, participants ranked which metaphor they would use if they were to use a metaphor in a conversation with non-quantum experts from most likely to least likely and justified their ranking. Finally, we asked participants if they knew of an alternative metaphor about quantum superposition or entanglement. If they answered “yes”, they were prompted to shortly describe the alternative metaphor, and rate it on accuracy and validity.

Expert insights: results

The survey ran between January 15th and March 15th, 2024 resulting in a total of n = 22 completed surveys. The majority of the participants were scientists

Table 5.1

Mean total scores (and SDs between brackets) for superposition and entanglement answered on a 7-point Likert scale. The total scores are an average of the scores on accuracy and validity, and are ordered from highest to lowest. The precise wordings per metaphor can be found in Table A17 in the Appendix.

Superposition		
#	Metaphor	Total (SD)
1	A coin spinning in the air	4.13 (1.86)
2	A radio producing a jumble of sounds	4.04 (2.94)
3	A cat, a vial of poison and a radioactive atom in a locked box	3.21 (2.59)
4	An artist dabbing his brush in multiple colours	3.04 (2.31)
5	A musician composing a music piece	2.25 (2.01)
Entanglement		
#	Metaphor	Total (SD)
1	A pair of dice	5.30 (1.89)
2	Two dancers performing a perfectly synchronized dance routine	3.80 (2.55)
3	A telepathic twin	3.35 (2.06)
4	Two compass needles that always point in opposite directions	3.15 (2.46)
5	Two clocks with perfectly synchronized second hands	2.90 (2.53)

working in a field involving quantum physics (n = 21), and one participant is an engineer. In total, 12 participants evaluated five metaphors about superposition, and 10 participants evaluated five metaphors about entanglement. The median completion time was 14 minutes 50 seconds. Experts indicated it was very likely (M = 5.68, SD = 1.36) that they would use a metaphor in a conversation with non-quantum experts to explain superposition or entanglement.

Table 5.1 shows that the coin metaphor scored highest for superposition (M = 4.13, SD = 1.86) and the dice metaphor for entanglement (M = 5.30, SD = 1.89). A complete overview of the experts' feedback per metaphor can be found in Table A18 in the Appendix. Based on these results, the metaphorical explanation condition thus included the coin metaphor for superposition and the dice metaphor for entanglement.

5.3.2 Design and procedure

The main study made use of an experimental design with 6 conditions: 1 factor with 3 levels (explanation type: metaphorical, non-metaphorical, no explanation) and 2 items (quantum phenomena: superposition and entanglement). Participants provided consent and then declared to not use any external sources, as we wanted to explicitly discourage the use of search engines and AI (see Meem et al., 2024). General information (age, gender, education) and control variables were asked, after which participants were randomly assigned to one of the 6 conditions. After reading the news article, participants were asked to answer questions on their perceived comprehension, actual comprehension, affect-based and cognition-based attitudes.

5.3.3 Participants

The experiment ran between January 29th and February 3rd, 2025 and resulted in a total sample of $n = 1{,}176$ participants. Participants were recruited by PanelClix (https://www.panelclix.nl/), an external panel service in the Netherlands. For each completed questionnaire in PanelClix, participants receive points ('clix') which they can exchange for money amongst others. The median time to complete the survey was 5 minutes and 50 seconds.

A total of $n = 9$ participants were excluded from the full analyses because they a) finished the survey within 90 seconds ($n = 4$); b) answered both the attention check question and the actual comprehension question incorrectly ($n = 3$); or c) reported being under the age of 18 ($n = 2$). As 36 participants failed to answer the actual comprehension question by mainly typing a letter or a non-existing word, they were excluded from only that part of the analysis. This resulted in a final sample of $n = 1{,}131$ participants for the analyses involving the actual comprehension variable and 1,167 participants for the remaining analyses.

The sample characteristics of the 1,167 participants closely matched the population statistics of the Netherlands (CBS, 2024). In terms of gender, $n = 596$ (51.1%) identified as male, $n = 568$ (48.7%) as female and $n = 3$ (0.3%) as other. Participants were between 18 and 88 years old ($M = 47.7$, $SD = 16.8$). In terms of education level, $n = 236$ participants (20.2%) reported having completed a low level of education, $n = 591$ (50.6%) reported an average level, and $n = 340$ (29.1%) reported a high level of education.

5.3.4 Dependent variables

Perceived comprehension. Perceived comprehension of the newspaper article was measured with 3 items (Miele & Molden, 2010). These are: *"How well do you feel you understand the news article?"* [1 = very poorly, 7 = very well], *"How certain are you that you will answer questions correctly about the news article?"* [1 = very uncertain, 7 = very certain], and *"How confused about the news article do you feel?"* [1 = not at all confused, 7 = very confused] (reverse coded). The three items were averaged into an index ($M = 4.38$, $SD = 1.20$, Cronbach's $\alpha = 0.73$).

Actual comprehension. To check whether participants remembered which quantum phenomenon was mentioned in the news article, we asked a control question. Participants were asked to select the phenomenon they had just read from a multiple-choice question (answer options: superposition, entanglement, tunnelling, decoherence, I don't know), and based on their answer, were asked to write in their own words what the selected phenomenon meant. If 'I don't know' was selected, the question was formulated as: *"Describe in your own words how particles behave at the smallest scale"*. We calculated the index on a scale from 0 to 4 based on the text provided by the participants (*M* $= 0.43$, *SD* $= 0.78$). A point was given for each of the following elements:

- For superposition:
  - (a) mention the connection with quantum;
  - (b) something can be A and B at the same time;
  - (c) a measurement has influence;
  - (d) after which a single state is left.
- For entanglement:
  - (a) mention the connection with quantum;
  - (b) there is a connection/correlation between parts;
  - (c) measurement of one part influences the other part;
  - (d) which is not dependent on the distance.

In addition to assigning points, participants' reuse of the metaphor was analysed. Both the index and the metaphor reuse were coded reliably, as intercoder agreement between two coders was perfect to near-perfect for almost all cases (see section A4.2 in the Appendix for full details on the intercoder reliability analysis).

Affect-based attitude. Affect-based attitude was measured with 7 items (van Giesen et al., 2018). These are: *"How do you feel about quantum technology after having read the news article? I feel..." ...joy, ...desire, ...fascination, ...satisfaction, ...fear* (reverse-coded), *...sadness* (reverse-coded), *...disgust* (reverse-coded) [1 = not at all, 7 = very much]. The seven items were averaged into an index (*M* $= 4.34$, *SD* $= 0.92$, Cronbach's $\alpha = 0.71$).

Cognition-based attitude. Cognition-based attitude was measured with 7 items (van Giesen et al., 2018). These are: *"What is your view on quantum technology after having read the news article? Quantum technology is...." ...useful, ...functional, ...beneficial, ...useless* (reverse-coded), *...harmful* (reverse-coded), *...disadvantageous* (reverse-coded), *...unusable* (reverse-coded) [1 = not at all, 7 = very much]. The seven items were averaged into an index (*M* $= 4.67$, *SD* $= 0.99$, Cronbach's $\alpha = 0.81$).

5.3.5 Control variables

We further measured five control variables, since we expected these to potentially influence our dependent variables. These were: *awareness of quantum, science news use, interest in new technology, faith in intuition* and *need for cognition*. All information regarding these variables is available in the Appendix A4.3.

5.3.6 Analysis and statistical procedures

Data were analysed with jamovi 2.3.28. Results of the two items (superposition and entanglement) were collapsed for the analysis to make generalizable claims on the effectiveness of (non-)metaphorical explanations across quantum phenomena. Randomization checks were performed to make sure that the participants were evenly distributed across the three conditions.[3] Participants were found to be evenly distributed across the three conditions for gender ($\chi^2(2) = 1.79$, $p = 0.408$), age ($\chi^2(6) = 3.98$, $p = 0.679$), level of education ($\chi^2(4) = 2.86$, $p = 0.581$), quantum technology awareness ($F(2, 1164) = 0.360$, $p = 0.698$), science news use ($\chi^2(2) = 0.608$, $p = 0.738$), interest in new technology ($F(2, 1164) = 0.808$, $p = 0.446$), faith in intuition ($F(2, 1164) = 1.04$, $p = 0.353$) and need for cognition ($F(2, 1164) = 0.110$, $p = 0.896$). Therefore, we did not include any of these variables as a covariate in the analyses.

[3]Note that for gender, the 'other' category was too small to meet the assumptions of the chi-square test of independence, which we therefore excluded.

To answer RQ1, four separate ANOVAs were performed using the explanation condition as independent variable and perceived comprehension, actual comprehension, affect-based attitudes, and cognition-based attitudes as dependent variables.

To answer RQ2 and RQ3, four separate mediation analyses were conducted using the jAMM module. We used the explanation type condition as the independent variable, perceived comprehension (for RQ2) and actual comprehension (for RQ3) as the mediator, and affect-based attitudes and cognition-based attitudes as the dependent variable. Confidence intervals were computed with the Bootstrap percentiles method using 5000 bootstraps.

5.4 Results

5.4.1 Main effects on the dependent variables

Statistically significant differences between the conditions were found for perceived comprehension ($F(2, 1164) = 8.49$, $p < .001$, $\eta^2 = 0.014$) and actual comprehension ($F(2, 1131) = 32.6$, $p < .001$, $\eta^2 = 0.055$). We found no statistically significant differences between the conditions for affect-based attitudes ($F(2, 1164) = 1.48$, $p = 0.23$) or cognition-based attitudes ($F(2, 1164) = 1.81$, $p = 0.16$).

Results of the pairwise comparisons with a Bonferroni correction showed that for perceived comprehension, the control group scored significantly higher than both the non-metaphorical group (mean difference = 0.32, $SE = 0.09$, $p < .001$) and the metaphorical group (mean difference = 0.29, $SE = 0.08$, $p = 0.002$). There was no significant difference between the metaphorical and non-metaphorical group (mean difference = -0.028, $SE = 0.09$, $p = 1.000$). For actual comprehension, the control group scored significantly lower than the non-metaphorical group (mean difference = -0.43, $SE = 0.06$, $p < .001$) and the metaphorical group (mean difference = -0.31, $SE = 0.05$, $p =< .001$). The difference between the non-metaphorical group and the metaphorical group was not significant (mean difference = 0.13, $SE = 0.06$, $p = 0.069$).

5.4.2 Mediation effects

Although no significant differences were found between the conditions on affect-based and cognition-based attitudes, mediation can still exist in the absence of a main effect (O'Rourke & MacKinnon, 2018). In performing the mediation analyses, we chose the control group as a reference group given the outcomes of the main effect analyses.

Table 5.3

Means (and SDs between brackets) by condition, based on the estimated marginal means estimated from the statistical model. Perceived comprehension, affect and cognition were measured on a 7-point Likert scale. Actual comprehension was measured on a scale from 0 to 4.

Comprehension				
Condition	Perceived	95% CI	Actual	95% CI
Control	4.58 (0.06)	[4.46, 4.69]	0.19 (0.04)	[0.11, 0.26]
Non-metaphorical explanation	4.26 (0.06)	[4.14, 4.38]	0.62 (0.04)	[0.54, 0.70]
Metaphorical explanation	4.29 (0.06)	[4.17, 4.40]	0.49 (0.04)	[0.42, 0.57]
Attitude				
Condition	Affect	95% CI	Cognition	95% CI
Control	4.39 (0.05)	[4.30, 4.48]	4.74 (0.05)	[4.64, 4.84]
Non-metaphorical explanation	4.36 (0.05)	[4.26, 4.45]	4.66 (0.05)	[4.56, 4.76]
Metaphorical explanation	4.28 (0.05)	[4.19, 4.37]	4.61 (0.05)	[4.51, 4.71]

Perceived comprehension of the news article as mediator

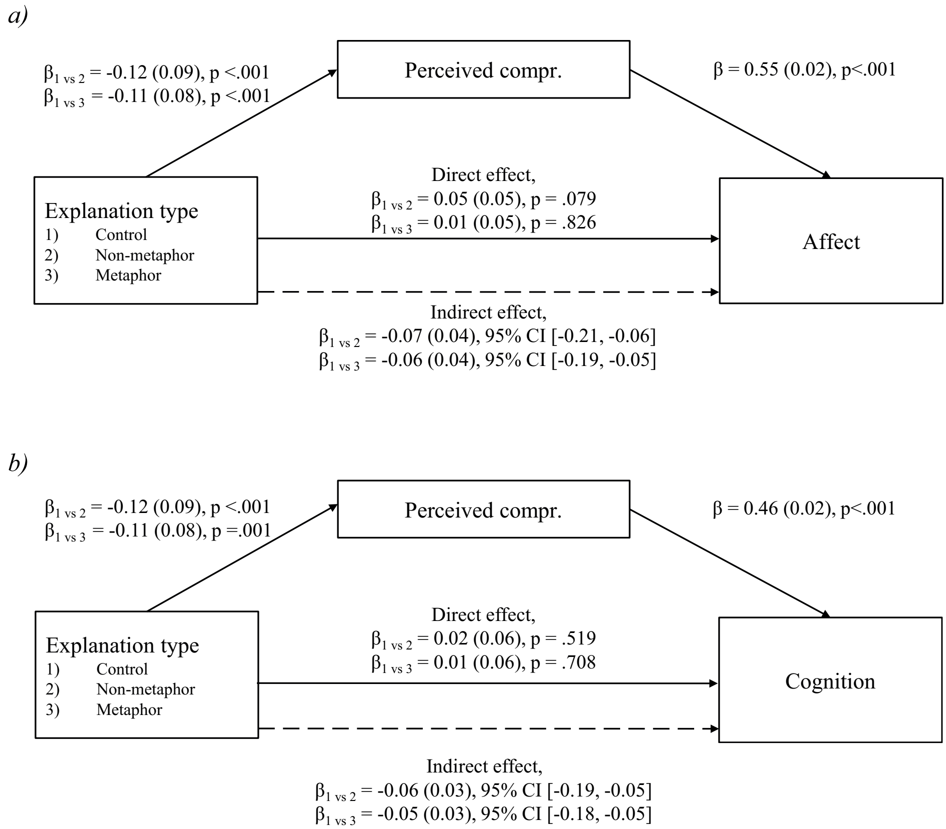
We found some evidence that perceived comprehension acts as a mediator between explanation type and both affect-based attitudes and cognition-based attitudes, as none of the confidence intervals for the tested indirect effects contained zero. Figure 5.2 shows the results (see Table A19 in the Appendix for the complete table).

As shown in Figure 5.2, we found a small but statistically significant decrease in perceived comprehension when participants received the non-metaphorical ($\beta = -0.12$, $p < .001$) or metaphorical explanations ($\beta = -0.11$, $p < .001$), compared to the control group. This indicates that both types of explanations lowered participants' feeling of understanding the news article. We furthermore found a strong statistically significant increase in both affect ($\beta = 0.55$, $p < .001$) and cognition ($\beta = 0.46$, $p < .001$) when participants scored higher on perceived comprehension. This indicates that there is a relationship between a higher perceived comprehension of the news article and feeling and viewing quantum technology more positively.

Given these two findings, the indirect effects found between explanation type and affect or cognition, with perceived comprehension as the mediator, were statistically

Figure 5.2

Visual representation of the results, depicting perceived comprehension as a mediator, with a) affect and b) cognition as dependent variables. Note that β_{1vs2} (β_{1vs3}) denotes the effect size of the non-metaphorical group (metaphorical group) with control as reference.



CHAPTER 5

significant ($p < .001$) but very small (β's ranged between -0.07 and -0.05). The direct effects, i.e. the effect of explanation type on affect or cognition when accounting for perceived comprehension, and the total effects were non-significant in all cases. This suggests that the effect of explanations on people's affect-based and cognition-based attitudes towards quantum technology is entirely dependent on how well they feel they understood a news article on the topic. Without a change in perceived comprehension, there would be no effect.

Actual comprehension of the quantum phenomenon as mediator

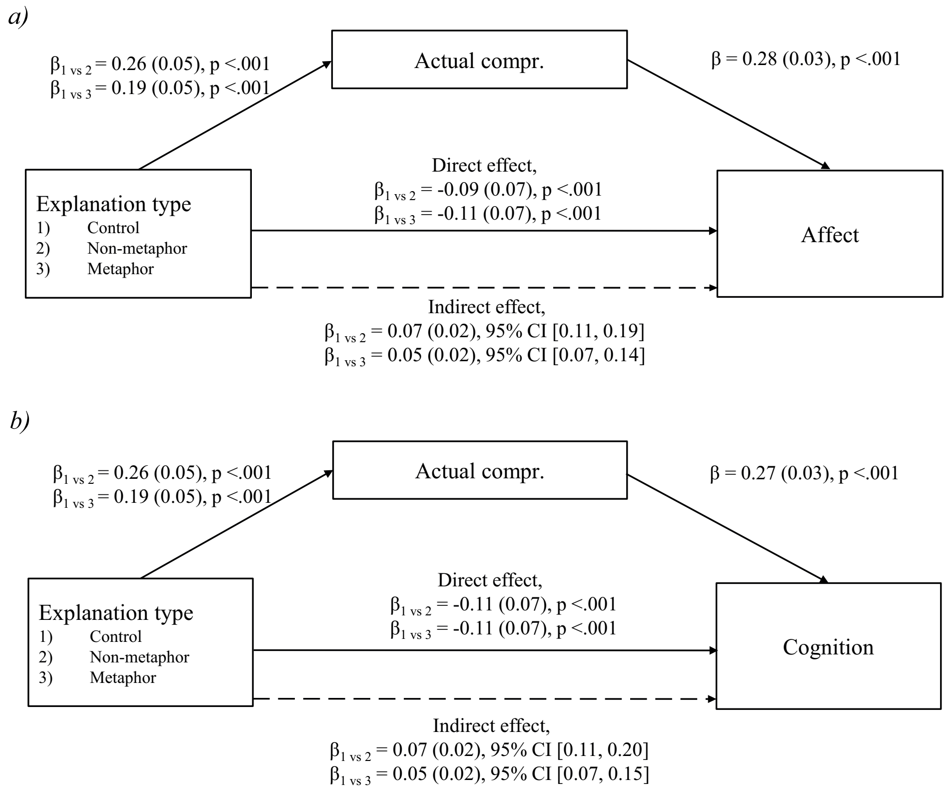
We also found some evidence that actual comprehension acts as a mediator between explanation type and both affect-based attitudes and cognition-based attitudes, as again none of the confidence intervals for the tested indirect effects contained zero. Figure 5.3 shows the results (see Table A20 in the Appendix for the complete table).

We found a small but statistically significant increase in actual comprehension when participants received the non-metaphorical ($\beta = 0.26$, $p < .001$) or metaphorical explanations ($\beta = 0.19$, $p < .001$), compared to the control group. We furthermore found a small statistically significant increase in both affect-based attitudes ($\beta = 0.28$, $p < .001$) and cognition-based attitudes ($\beta = 0.27$, $p < .001$) from actual comprehension. This indicates that there is a relationship between a higher actual comprehension of the quantum phenomenon and feeling and viewing quantum technology more positively.

Given these two findings, the indirect effects between explanation type and affect or cognition, with actual comprehension as the mediator, were statistically significant ($p < .001$) but very small (β's ranged between 0.05 and 0.07). The direct effect, which is the remaining effect after accounting for actual comprehension as a mediator, revealed a small negative effect (β's between -0.11 and -0.09). The total effects were non-significant. Since the indirect and direct effects have opposing signs, finding a mediating effect in this case while the total effect is non-significant is called inconsistent mediation (O'Rourke & MacKinnon, 2018). This suggests that while explanations may increase people's affect-based and cognition-based attitudes towards quantum technology by improving their understanding of quantum phenomena (i.e., actual comprehension), this positive effect is counteracted by a direct negative effect of explanation type on affect-based and cognition-based attitudes. There may be other mechanisms at play that result in such a counteracting effect.

Figure 5.3

Visual representation of the results, depicting actual comprehension as a mediator, with (a) affect and (b) cognition as dependent variables. Note that β_{1vs2} (β_{1vs3}) denotes the effect size of the non-metaphorical group (metaphorical group) with control as reference.



5.5 Discussion

This study examined, through a large-scale experiment, how (non-)metaphorical explanations of a quantum phenomenon influenced people's perceived comprehension of a news article about quantum technology, their actual comprehension of a quantum phenomenon, and their attitudes towards this emergent technology.

5.5.1 Effects of explanation type on comprehension

We found that including an explanation of a quantum phenomenon – regardless of whether it was metaphorical or non-metaphorical – led to lower perceived comprehension scores of the text, while actual comprehension scores of the quantum phenomenon were higher. The findings that metaphors can lead to higher perceived comprehension (Reijnierse et al., 2025) or enhance people's overconfidence (A. J. Jaeger & Wiley, 2015; Wiley et al., 2018) was thus not apparent in our study. The opposite even emerged, where (non-)metaphorical explanations had a detrimental effect on participants' perceived comprehension of the text, but improved their actual comprehension of the quantum phenomenon, compared to a control condition. It should be noted that actual comprehension scores were low in all conditions (≤ 0.62), suggesting that people did not grasp the phenomenon well.

It is important to note that we measured perceived comprehension for the text as a whole, but actual comprehension specifically for the quantum phenomenon. Perhaps the fact that explanations reduce perceived comprehension of the text indicates an information overload, where the length and amount of information make a text seem more complex. In contrast, we found that explanations contribute to an improved actual comprehension of a quantum phenomenon. This makes sense, because without an explanation it is conceivable that people do not know what superposition or entanglement entails (also note the low awareness for quantum technology, see Figure A8), and therefore cannot answer a question about it correctly.

We found no differences between metaphorical and non-metaphorical explanations on actual comprehension, consistent with Alexander and Kulikowich (1991) and Braasch and Goldman (2010), but contrasting others (Glynn & Takahashi, 1998; A. J. Jaeger & Wiley, 2015; Yanowitz, 2001). A main difference is that we ensured the phenomenon was explained only once in the metaphor condition, while previous work often used metaphor-enhanced texts that lead to double explanations of a phenomenon. Furthermore, our actual comprehension question focused specifically on the quantum phenomenon, whereas other studies also tested comprehension of parts unrelated to the metaphor (see e.g., Alexander & Kulikowich, 1991; A. J. Jaeger

& Wiley, 2015). Finally, different ways to measure actual comprehension exist, for instance through closed multiple-choice questions (Alexander & Kulikowich, 1991), open recall questions (Glynn & Takahashi, 1998), inference questions (questions about 'what happens if something in the system changes'; Yanowitz, 2001) and prompting to write a full essay (Braasch & Goldman, 2010; A. J. Jaeger & Wiley, 2015). These different ways probably also lead to different comprehension scores, with some tapping into more shallow levels of comprehension and others into deeper ones (see also Bernholt et al., 2023).

A closer look at the actual comprehension answers furthermore provides an interesting insight about the terms 'superposition' and 'entanglement'. Some participants wrote that superposition is about a competitive (market) position ($n = 46$, 8.0%) and entanglement about intertwining things, such as weaving, mixing or melting ($n = 39$, 6.6%). While the technical terms 'superposition' and 'entanglement' might not be considered metaphorical to quantum scientists (Beger & Smith, 2020), they may be processed differently by people outside the quantum field. Furthermore, only 13.1% of the participants in the metaphor condition reused the provided metaphors (a coin spinning in the air: $n = 33$, 16.6%; rolling a pair of dice: $n = 19$, 9.6%). Perhaps the metaphorical explanation remained too abstract or was too brief to fully understand the quantum phenomenon.

5.5.2 Effects of explanation type on attitude

We found no differences between the three conditions for affect-based attitudes and cognition-based attitudes. This differs from the small persuasive effect of metaphors compared to literal messages as found in meta-analyses (O'Keefe & Hoeken, 2021; Sopory & Dillard, 2002; Van Stee, 2018). The target domain was likely too unfamiliar with low quantum technology awareness scores (see Figure A8), making the cognitive effort required to process the metaphor too great (Sopory & Dillard, 2002; Van Stee, 2018).

Previous research suggests that using metaphors to explain quantum phenomena, such as superposition and entanglement, might improve attitudes towards quantum technology (Grinbaum, 2017). However, in our study, attitudes towards quantum technology were positive across conditions, regardless of whether a quantum phenomenon was explained. This suggests that resistance, found with other emergent technologies (Druckman & Bolsen, 2011; Kurath & Gisler, 2009), may currently not apply for quantum technology. Given the low awareness of quantum technology, it is plausible these positive attitudes formed during the survey (see also Druckman & Bolsen, 2011; van Giesen et al., 2018). Apparently, reading a neutral-to-slightly-positive article about quantum technology is enough to form these attitudes, regardless of an additional explanation about underlying phenomena.

5.5.3 Comprehension as a mediator between explanation type and attitudes

Results of the mediation analyses suggest that explanations have a very small negative indirect effect on people's attitudes towards quantum technology, due to the fact that people feel they understood the news article less. This is consistent with Akin et al. (2021), who found that people's beliefs about their own knowledge of a technology were more influential in shaping their attitudes than their actual knowledge. While we also found a very small positive indirect effect of explanations on attitudes mediated by actual comprehension, this was counteracted by a direct negative effect. Apparently, improving people's actual comprehension of the underlying quantum phenomena does not necessarily result in more positive views towards quantum technology, as there could be other mechanisms at play that counteract the positive effect on comprehension.

In addition, and in contrast with what Grinbaum (2017) advocated, the type of explanation, metaphorical or non-metaphorical, did not lead to different outcomes on comprehension and therefore on attitudes. One possible explanation for this is that the metaphors used in our study, although deemed most accurate and valid, did not evoke a sufficiently vivid image in people's minds (Wyer Jr & Shrum, 2015). It could well be that with a different metaphor attitudes would have been affected more, for example with the famous metaphor of Schrödinger's cat. While experts in preparation of the experiment acknowledged that the metaphor is very well-known (see also Van de Merbel et al., 2024) and therefore may resonate better, some experts pointed out that the metaphor is incorrect and too complicated to bring across.

5.5.4 Resistance to metaphor

Finally, we want to point out an interesting additional finding: some experts in preparation of the experiment indicated that the metaphors made the quantum phenomena unnecessarily complicated and mysterious, creating only more confusion. One expert even emailed us afterwards saying that their "strong feeling is that it is dangerous to use a metaphor for such a profound phenomenon". This aligns with the body of research that metaphors can cause resistance. Such a comment also ties in with Feynman's quote that quantum phenomena are too complex to explain (Feynman, 1967), which could be bad for the democratization of quantum technology (Seskir et al., 2023).

5.5.5 Practical implications

In this study, we have shown that explanations of quantum phenomena in a news article affect people's comprehension, which subsequently mediates attitudes towards quantum technology. We recommend that, if the goal of a news article is to increase people's feeling that they have understood the text, journalists better skip the explanation of counterintuitive quantum phenomena. De Jong (2025) has taken this a step further by arguing that quantum phenomena should not be explained to a general public, but there should be an increased focus on the functional capacities of quantum technology to lower the barrier to engage in ethical discussions about quantum.

Our recommendation changes if the goal is to increase people's actual understanding of the underlying quantum phenomena of quantum technology. Explanations help to increase actual comprehension of quantum phenomena, but our findings suggest that there is no additional benefit of using metaphors to explain counterintuitive quantum phenomena.

CHAPTER 6

Conclusion

6.1 Introduction

This dissertation focused on investigating the public communication around quantum science and technology that may affect public engagement. To this end, we conducted a series of studies. First, we analysed the occurrence of potential popularisation issues surrounding quantum science and technology in English TEDx talks and Dutch newspaper articles. Second, we tested the effect of these potential popularisation issues on people's engagement with quantum technology. Finally, we explored whether metaphors make key quantum phenomena more comprehensible and whether this, in turn, influences attitudes towards quantum technology.

This chapter gives a brief summary of the main findings of each study, presents the implications for research and practice, and describes limitations and future research avenues. It concludes with four recommendations for science communication researchers and four recommendations for science communicators based on the implications of this dissertation's findings.

6.2 Summary of the insights of this dissertation

6.2.1 Occurrence of four potential popularisation issues

In the scientific literature, it is argued that potential popularisation issues surrounding quantum science and technology occur in public communication. These issues are:

1. framing quantum science and technology as something enigmatic (Coenen et al., 2022; Vermaas, 2017);
2. skipping the underlying quantum phenomena when explaining what quantum technology entails (Grinbaum, 2017);

3. using a narrow instead of a wider public good frame (Roberson et al., 2021);
4. focusing on the domain of quantum computing at the expense of the other two quantum technology domains (i.e., quantum communication and quantum sensing & metrology; Roberson et al., 2021).

No empirical research had investigated whether these potential issues actually occur in public communication about quantum science and technology. Therefore, **Chapter 2** and **Chapter 3** set out to address this question. Using a quantitative content analysis, Chapter 2 analysed the occurrence of the four potential issues in 501 English-language TEDx talks, and Chapter 3 analysed these issues in 385 Dutch-language newspaper articles.

The results demonstrated that the four potential issues occur very similarly in English TEDx talks and Dutch newspaper articles.[1] First, *the spooky and enigmatic frame* occurred in almost a quarter of both datasets (23% in TEDx talks and 24% in newspaper articles). The frame was therefore found to be apparent, but did not appear in the majority of the TEDx talks and the newspaper articles.

Second, we analysed the occurrence of *explanations for three quantum phenomena*: superposition, entanglement and contextuality. In line with Grinbaum's (2017) concern, we analysed how often a quantum phenomenon explanation was present when quantum technology itself was mentioned. We found that around half of the analysed materials with a reference to quantum technology contained at least one explanation for one of the key quantum phenomena (54% for English TEDx talks and 51% for Dutch newspaper articles). While this occurrence was more common than expected based on Grinbaum's (2017) concern, still a substantial amount of the TEDx talks and the newspaper articles do not provide an underlying explanation of these three key phenomena.

Third, we analysed whether the uses and implications of quantum technology in and on society were reflected upon in a *wider sense or a more narrow sense*. Reference to how quantum technology can solve problems or improve people's lives (the social progress frame, which is considered a wider public good frame) was hardly found in both datasets (7% in English TEDx talks and 3% in Dutch newspaper articles). However, there was also hardly any reference to how quantum technology can realise economic development or lead to competition (the economic development/competitiveness frame, which is considered a narrow public good frame; 5% in English TEDx talks and 9% in Dutch newspaper articles). The concern of Roberson et al. (2021) was additionally analysed by examining the occurrence

[1]Percentages depicted in this section are rounded to whole numbers.

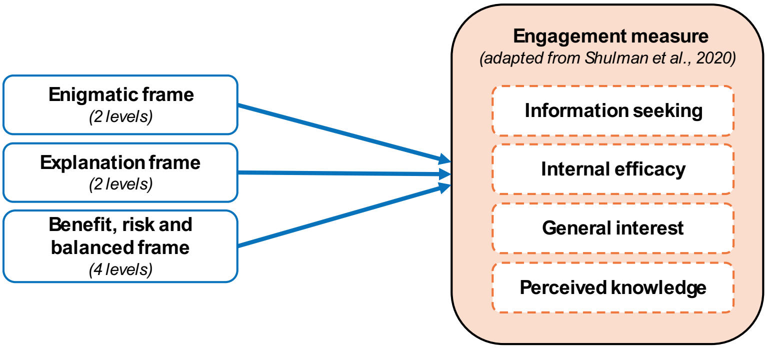
of the benefit frame versus the risk frame divide, where a wider public good frame constitutes a reflection on both benefits and risks. Results demonstrated that benefits were emphasized approximately six times more often than risks (benefits were mentioned in 34% of English TEDx talks and 33% of Dutch newspaper articles, while risks appeared in only 5% and 6%, respectively). This demonstrated that, as a wider sense of how quantum technology can cause harm is lacking, the wider public good frame does not really seem to exist in both datasets.

Finally, both datasets showed *a focus on the domain of quantum computing & simulation*, as it was referred to more often than the other two quantum technology domains. The quantum computing & simulation domain appeared in 24% of the English TEDx talks and 40% of the Dutch newspaper articles. This was followed in both datasets by the quantum communication domain with a 6% mention in English TEDx talks and 9% mention in Dutch newspaper articles. Finally, the domain of quantum sensing & metrology hardly occurred as it was referenced in only 2% of the English TEDx talks and 1% of Dutch newspaper articles. This is surprising given that the latter technologies are expected to reach commercial applications much earlier than quantum computers (C. L. Degen et al., 2017, but Chapman et al., 2024 argue this low focus on quantum sensors is because quantum sensors do not promise new capabilities, while the domains of quantum computing & simulation and quantum communications do).

When analysing the English TEDx talks, an additional potential issue appeared that we had not found in the scientific literature at the time of the study (but see Bondani et al., 2024): 15% of the talks were found to contain a mystical viewpoint, i.e., a pseudoscientific, inaccurate picture that can potentially result in misconceptions about quantum technology's applications. This was surprising given that the TEDx guidelines explicitly discourage speakers to present such viewpoints ('TEDx Content Guidelines', n.d.). Due to its frequency in the TEDx talks, this potential issue was added to the analysis of Chapter 3, but only 3% of the newspaper articles were found to make reference to a mystical viewpoint. This showed that, perhaps, most journalists want to ensure that the ideas they present about quantum science and technology fit inside widely accepted scientific paradigms, thereby aligning their coverage with views from the scientific community (see Bennett's 'indexing' theory; Bennett, 2016).

Figure 6.1

Conceptual model of the between-subjects experiment in Chapter 4.



6.2.2 Effect of frames on people's engagement with quantum technology

The second aim of this dissertation was to investigate the effect of the potential popularisation issues, which were quantified in Chapters 2 and 3, on public engagement with quantum technology. Therefore, **Chapter 4** presented an experiment to investigate this second aim.

To measure engagement, we adapted the scientific engagement scale from Shulman et al. (2020) for the context of quantum technology. This measure included four variables: 1) participants' intention to seek additional information on quantum technology (information seeking); 2) their belief about their own ability to understand and engage with quantum technology information (internal efficacy); 3) their general interest in quantum technology (general interest); and 4) their confidence in their knowledge of quantum technology (perceived knowledge). Figure 6.1 provides an overview of the conceptual model of the study.

A linear multiple regression analysis showed:

1. no significant effect of the enigmatic frame on any of the engagement variables;
2. a significant positive effect of explaining a quantum phenomenon on general interest in quantum technology;
3. a significant positive effect of the benefit frame on participants' belief about their own ability to understand and engage with quantum technology information;

4. and a significant negative effect of the balanced frame on people's confidence in their own quantum technology knowledge.

These findings yielded important new insights into whether the potential issues are actual issues with respect to self-reported engagement. They showed that explaining quantum phenomena and emphasizing the benefits of quantum technology may be helpful for engaging people with quantum technology, while the enigmatic frame seemed to neither increase nor harm engagement. In addition, the balanced frame reduced people's confidence in their quantum technology knowledge. This revealed an interesting tension, as Roberson et al. (2021) argued that for the greatest public benefit, it is important to reflect broadly on both the benefits and risks. In our view, this ethical consideration is more important to consider in public communication about quantum technology than its potential drawbacks.

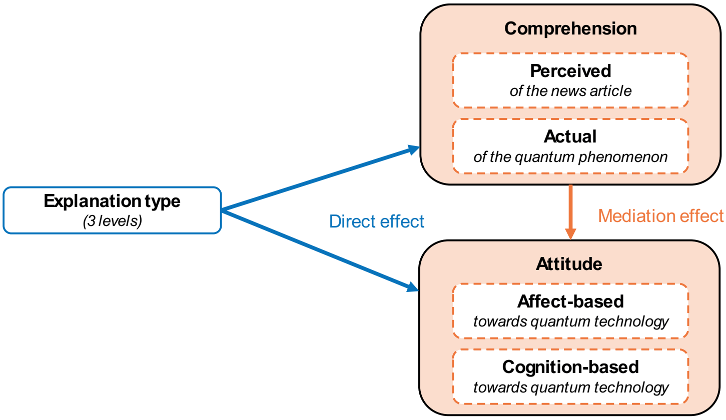
6.2.3 Effect of metaphors on comprehensibility of quantum phenomena, and their (subsequent) effect on attitudes

While Chapter 4 already examined how an explanation of a counterintuitive quantum phenomenon influences dimensions of engagement, **Chapter 5** explored the potential issue raised by Grinbaum (2017) in more detail: that, without a comprehension of quantum technology's underlying quantum phenomena, public attitudes toward quantum technology become more negative. Grinbaum (2017) suggested the use of metaphors to overcome this issue. To investigate this, Chapter 5 tested to what extent metaphors make quantum phenomena more comprehensible, and whether that consequently influences people's attitudes towards quantum technology.

Chapter 5 used an experiment, preceded by a small-scale study among Dutch quantum experts to design accurate stimulus material. The small-scale study aimed to identify the most accurate metaphors for communicating key quantum phenomena, specifically superposition and entanglement, to non-experts. To achieve this, $n = 22$ native Dutch-speaking quantum experts evaluated five metaphors about superposition or entanglement on accuracy and validity in a survey. The metaphors were generated by ChatGPT 3.5, a widely adopted and accessible large language model, to respond to calls within the science communication research community to evaluate the accuracy of AI-generated scientific explanations (Schäfer, 2023). The metaphor for superposition that was rated most accurate compared it to a coin spinning in the air, which is heads and tails at the same time until the coin hits the table. The metaphor for entanglement compared it to rolling a pair of dice, where if one die is rolled, the outcome of the other die is predetermined, even if it is on the other side of the gambling table. Because these two metaphors were considered the

Figure 6.2

Conceptual model of the between-subjects experiment in Chapter 5.



most accurate by quantum experts, they were used in the main experiment.

The experiment in Chapter 5 used 1 factor (explanation type: metaphorical, non-metaphorical, no explanation) and 2 items (quantum phenomenon: superposition, entanglement). A total of n = 1,167 participants representative of the Dutch adult population were asked to read a fictitious news article that either included a metaphorical, non-metaphorical, or no explanation at all about superposition or entanglement. Afterwards, we measured four variables: 1) participants' beliefs about their understanding of the news article (perceived comprehension); 2) their actual understanding of the quantum phenomenon (actual comprehension); 3) their emotions and feelings towards quantum technology (affect-based attitude); and 4) their thoughts and beliefs about quantum technology (cognition-based attitude). Figure 6.2 provides an overview of the conceptual model of the experiment.

Results demonstrated that, regardless of whether an explanation of a quantum phenomenon was metaphorical or non-metaphorical:

1. the explanation led to significantly lower scores on participants' perceived comprehension of the news article;
2. participants' actual comprehension of the quantum phenomenon was significantly higher;
3. no differences were found between the three conditions (metaphorical, non-metaphorical, no explanation) on attitudes.

Since previous research suggests that there is a relationship between comprehension and attitude (Akin et al., 2021; Wyer Jr & Shrum, 2015), we examined whether this relationship also applies in the context of our study. Results of the mediation analyses demonstrated statistically significant, but very small effects. They showed that, regardless of whether an explanation was metaphorical or non-metaphorical:

1. the explanation lowered participants' feelings of understanding the news article, which led to a decrease in their affect-based and cognition-based attitudes;
2. the explanation increased participants' actual understanding of the quantum phenomenon, which led to an increase in their affect-based and cognition-based attitudes, but this was counteracted by a direct negative effect.

The findings reported in Chapter 5 suggest that when a news article aims to increase people's feeling of having understood its content, science communicators better skip explaining counterintuitive quantum phenomena of quantum technology. However, when the goal is to increase people's actual comprehension of the quantum phenomena that underlie quantum technology, explanations do help. Metaphorical explanations seem to have no additional benefit over non-metaphorical explanations in this context, in contrast to what Grinbaum (2017) suggested.

6.3 Implications of the insights of this dissertation

The studies presented in this dissertation connected multiple disciplines, and are among the first to explore the emerging field of research at the intersection of quantum technology and society. In this section, we examine both the implications of our findings for the science communication research field and its practical implications for science communicators.

6.3.1 Implications for the science communication research field

First of all, the studies in this dissertation showed that claims made about potential issues in science communication should be examined empirically. While researchers might intuitively assume that a particular frame is used very frequently, only empirical data can offer true insight into whether that is actually the case. For example, this dissertation revealed that - contrary to concerns in the literature (Roberson et al., 2021; Seskir et al., 2023) - the focus on a quantum race between countries is rarely mentioned in English TEDx talks and Dutch newspaper articles, and therefore is likely having less of an effect on people's perceptions. This dissertation thus demonstrated that empirical investigations on the frequency of certain “issues” in materials aimed at non-expert audiences truly clarifies which concerns may represent genuine problems and which rarely occur and therefore may not pose as major obstacles as expected.

Secondly, the content-analytical studies in this dissertation focused on two formats: English TEDx talks (Chapter 2) and Dutch newspaper articles (Chapter 3). These two formats differ in several ways, for example in the type (presentations vs. news articles), the language (English vs. Dutch), the creator of the content (non-expert or expert speaker vs. journalist), and the audience (local communities and internet users watching the talk on YouTube vs. readers of Dutch newspapers). Also the word length differs, as transcripts of the TEDx talks averaged around 2,400 words, while the newspaper articles in our sample averaged only 956 words. In this dissertation, we have thus been able to gain insight into the occurrence of the potential popularisation issues from literature in two very different types of communication. Our results showed that the occurrences in these two communication types are very comparable, potentially suggesting a trend in public communication about quantum technology. The reason why we were able to discover these similarities and differences between the two types of communication is that we carefully developed a reliable codebook for the identification of potential popularisation issues surrounding quantum science and technology. To develop this codebook, we formulated concrete definitions and clear coding instructions. Through elaborate discussions between multiple coders and the execution of subsequent intercoder reliability tests, we were able to determine the reliability of the codebook, which - as we have shown - can be applied to identify the potential popularisation issues across different communication forms. To allow the further use of this codebook and in light of open science, the materials in this dissertation have been deliberately shared openly in the journals in which the works are published and on the Open Science Framework (OSF).

Furthermore, quantum technology is still in an early stage of development, has not (yet) had a large-scale societal impact, and remains largely unfamiliar to the public (Chapter 5). This dissertation demonstrated that even for topics about which people know very little, the type of information provided can already shape their views of the topic (see also Druckman and Bolsen, 2011 and Van Giesen et al., 2015, amongst others). Even brief, one-time exposures, such as a few sentences (Chapter 4) or a short news article (Chapter 5), can lead to significant differences in outcomes such as interest or comprehension. In the context of emergent technologies, of which the public is still largely unaware (Cobb & Macoubrie, 2004; Scheufele & Lewenstein, 2005) but which can have major societal consequences, communication choices thus seem to matter for its public engagement (see also Reincke et al., 2020).

Finally, as Retzbach and Maier (2015) also noted, studies examining the effect of frames on various aspects of public engagement with science remain sparse. In the context of new technology, most studies focus on the effect of frames on public support (see e.g., Achterberg, 2014; Cobb, 2005; Druckman & Bolsen, 2011; Palm et al., 2025). While support is indeed an important variable to study, given that it is one of the goals of public engagement (Van Dam et al., 2020), there are also other important reasons to engage the public with a new technology. For instance, public engagement may also lead to more socially robust solutions (Roberson et al., 2021) and is in line with a democratic perspective (Van Dam et al., 2020). This dissertation demonstrated that measuring the effects of frames on variables that are not directly about public support can provide important insights into engagement (Chapter 4).

6.3.2 Practical implications for science communicators

Besides research-related implications, the results in this dissertation also have implications for researchers, journalists, communication officers and other actors who wish to communicate about quantum technology to a broader audience (we will refer to these actors as science communicators in the remainder of this chapter).

First of all, quantum experts most often framed quantum science and technology as something spooky and enigmatic in TEDx talks (Chapter 2). Our results showed that emphasizing the enigmatic nature of quantum science a single time in a text does not seem to influence people's self-reported engagement with quantum technology (Chapter 4). This suggests that in science communication about quantum science and technology, the spooky and enigmatic frame has no clear advantage or disadvantage in engaging the public.

Second, our results showed that whether or not to include explanations of counterintuitive quantum phenomena in communications to a broader audience depends on the goal of the communication. If the goal is to increase interest in quantum technology, and engagement with quantum technology in general, explaining a counterintuitive quantum phenomenon may help (Chapter 4). Furthermore, a short explanation may result in a (slight) increase in actual understanding of the quantum phenomenon in question (Chapter 5). However, if the goal is to make the audience feel that they have understood the communication itself about quantum technology, it may be better to avoid explanations of the underlying counterintuitive quantum phenomena (Chapter 5). Still, science communicators do not need to fear that explaining a quantum phenomenon in communication has a large negative effect on public attitude. While our results did show that a quantum phenomenon explanation has a negative effect on attitudes towards quantum technology through a decrease in perceived comprehension of the news article, this effect is very small and probably practically negligible - especially given the generally positive attitudes toward quantum technology that were found throughout our sample (Chapter 5).

Metaphors do not appear to offer an additional advantage over non-metaphors in explaining counterintuitive quantum phenomena (Chapter 5). Although previous studies have advocated for the use of metaphors in public communication about quantum science and technology (e.g., Grinbaum, 2017; Hilkamo & Granqvist, 2022), our results showed no significant differences in participants' comprehension or attitudes when exposed to metaphorical versus non-metaphorical explanations of a quantum phenomenon in a news article. This suggests that effective communication about quantum science and technology is not necessarily dependent on the use of metaphor. However, our small-scale expert study suggested that some metaphors may be too complex or mysterious to convey, which could lead to a wider gap between what experts consider good science communication and what resonates with the general public.

Finally, we found that quantum computing was discussed much more than other quantum technologies, suggesting a narrow focus on the field (Chapters 2 and 3). Furthermore, we found a tendency among TEDx speakers and journalists to communicate the benefits of quantum technology but ignore the risks (Chapters 2 and 3). This may contribute to a too narrow reflection of the possible impact of the quantum technology field as a whole on society (see also Roberson et al., 2021). The results of our experiment suggest that such a focus on communicating the benefits of quantum technology can increase people's confidence in their own ability to understand and engage with information about quantum technology (Chapter 4). Yet, our results also showed that presenting both the benefits and risks may reduce people's confidence in their own knowledge about quantum technology (Chapter 4). It has been suggested, however, that a broad reflection on the potential benefits and risks of quantum technology is necessary in order to maximize its benefits while minimizing its risks (see Roberson et al., 2021). From this perspective, the decrease in people's perceived knowledge does not outweigh the importance of such a broader discussion.

6.4 Limitations and future research avenues

This dissertation is among one of the first works to connect the fields of science communication and quantum technology. Yet, many more questions remain on how to establish a good connection between quantum and society. This section discusses the main limitations of this dissertation and provides suggestions for future research.

6.4.1 A focus on one-way communication

First, if we look critically at this dissertation, the focus has been more or less on one-way communication. While the first role of public engagement according to Reincke et al. (2020) is meaningful information sharing, and engagement has consistently underpinned the way in which the research was set up, actual quantum technology engagement and dialogue have not been examined. In order to ensure real mutual learning between quantum scientists and society, the two remaining roles proposed by Reincke et al. (2020) - listen to, and learn from, each other, and investing in relationships - should also be addressed.

Future research could explore the two remaining roles for experts and science communicators in achieving meaningful engagement with quantum technology (Reincke et al., 2020), for example, by setting up and evaluating quantum engagement initiatives (see Busby et al., 2017). In doing so, it is important to try to avoid the pitfalls that revert such a two-way communication initiative into a one-way model (Bauer & Bogner, 2020; Kurath & Gisler, 2009). Bauer and Bogner (2020), for instance, noted that engagement events on synthetic biology often remained academic and rational, dividing the scientists and the 'illiterate' public. Therefore, quantum engagement initiatives should create space for emotional responses and controversial positions (Bauer & Bogner, 2020). In addition, scientists should be encouraged to raise their own questions and concerns instead of merely answering the questions of others (Reincke et al., 2020): for example, how could criminal organizations exploit quantum technology (Vermaas et al., 2019) or how could quantum technology further widen the digital divide between regions (Ten Holter et al., 2022)?

6.4.2 Predefined set of frames

Chapters 2 and 3 used a predefined set of frames to analyse the occurrence of four potential popularisation issues found in the scientific literature. However, this method also introduces a limitation, as we may have overlooked potentially interesting frames for public engagement, such as those discussed in papers published after our research was conducted (e.g., the incomprehensibility frame; Seskir et al., 2023).

Future research could therefore use a top-down approach to explore additional potential popularisation issues that were published after our study was conducted. This approach could be combined with an "open category" format, to identify potentially new frames that are frequently encountered in quantum communication and have not (yet) been mentioned in the literature (see Pöhlmann et al., 2024 for a first bottom-up study in this direction). The effect of the frames that appear most frequently in public communication about quantum technology should then be tested on outcome variables such as engagement.

6.4.3 Experimental limitations

The experiments in Chapters 4 and 5 relied on self-reported measures, such as participants' stated intentions. While this is an easy way to obtain information about participants' intentions and attitudes, these measures may not accurately reflect real-world behaviour. People may give answers based on what they assume is socially desirable, such as claiming that they will seek further information about quantum technology because they believe it is expected of them (see e.g., Neuberger, 2016 who found that participants overreport on their information seeking behaviour). To assess real-world behaviour such as actual information seeking, future research could, for instance, include an option at the end of a survey allowing participants to request for more information about quantum technology.

The experiments in Chapters 4 and 5 furthermore made use of a single text that presented the condition under study once. This provides a good indication of the effect a one-time presentation of particular information has on participants. For example, Chapter 4 showed that a brief, single presentation of the spooky and enigmatic frame had no significant effect on participants' self-reported engagement. A limitation of this approach is, however, that it does not reveal how repeated exposure to a frame might influence participants, whilst, for example, the spooky and enigmatic frame may be emphasized more often in communication about quantum science and technology. A first step toward understanding the effects of repeated exposure would be to conduct a study in which different groups are exposed to a different number of repetitions of the condition, or to conduct a longitudinal study in which participants are exposed to a certain condition multiple times over a specific period (see e.g., Retzbach & Maier, 2015).

In addition, the experiments in Chapters 4 and 5 focused on the effect of message characteristics on a representative sample of the Dutch adult population. While this provides a good overview of the effects of certain communication features on the Dutch public in general, it does not explore the impact on specific groups within society that may differ in individual characteristics. Such characteristics, like trust in science (Achterberg, 2014) or individuals open to new or inconsistent information (Retzbach & Maier, 2015), can influence the effect of frames. Future research could explore this in more depth by identifying how individual characteristics influence the effect of certain frames.

Finally, the experiments presented in Chapters 4 and 5 in this dissertation made use of online panel services. An advantage of these services is that they allow for the relatively fast recruitment of a sample that is broadly representative in terms of age, gender, and education level. However, there are also limitations to using online panel services (see e.g., Kleijngeld et al., 2004). One of the criticisms is that participants may be less engaged with the research when they are primarily motivated by financial rewards (note that this concern does not apply to KiesKompas, which does not offer such rewards). Moreover, online panels are not fully representative of the Dutch population, as certain groups are systematically excluded such as individuals with limited digital skills. A study by Kleijngeld et al. (2004) demonstrated good consistency and reliability of the data of PanelClix, but with developments such as ChatGPT it remains an open question whether those findings still hold (Meem et al., 2024). To address these limitations, future research should address the research questions in this dissertation using other approaches than online panel services, such as offline surveys in lab settings, in-depth interviews, or focus groups.

6.4.4 A quantum technology hype

A key insight from this dissertation is that the potential benefits of quantum technology are mentioned about six times more often than its potential risks in English TEDx talks (Chapter 2) and Dutch newspaper articles (Chapter 3) – suggesting skewed communication. Such a strong focus on potential benefits of a new technology may possibly indicate hype, where hype is defined as that potential benefits are exaggerated and its risks understated (Caulfield & Condit, 2012; Roberson, 2020).

We, nor other empirical research, have (yet) examined whether there is a widespread quantum technology hype. Still, some have argued that there is, such as scientists who state that no one has yet come close to building a quantum device capable of solving practical problems (Greene, 2022), and that many of the promises made about the impact of quantum technology are either very long-term or "really far-fetched" (Ezratty, 2022, p 8). Also teachers have stated that media hype surrounding quantum technology is influencing their teaching both in terms of attracting students who arrive with preconceptions and of shaping the content of their course (Meyer et al., 2023). However, other scientists have argued that there is an anti-hype; for example, one physicist wrote on X that "quantum computing is simultaneously overhyped and underhyped. Schrödinger's hype, if you will" (Fitzsimons, 2022). Future research should examine the amount of quantum technology hype by evaluating inaccuracies about methods or result interpretations, similar to Bubela and Caulfield (2004) analysis of hype in media coverage of genetic research.

6.4.5 Perspectives from the Global South

The studies in this dissertation mainly focused on the Global North (Chapter 2), and specifically on the Netherlands (Chapters 3-5). The Global North, and the Netherlands in particular, are interesting to study, as many countries in this region are investing heavily in quantum technology, and the Netherlands has emerged as one of the key players in the field (Gaida et al., 2023). In addition, the Dutch National Quantum Agenda, published in 2019, explicitly mentions the objective to research the societal impact of quantum technology at an early stage to ensure a good connection between quantum technology and society (Stichting Quantumdelta NL, 2020). However, by studying this group, we also touch upon a broader limitation in science communication research, where perspectives from the Global South are consistently underrepresented (Guenther & Joubert, 2017; Massarani, 2015). In the intersection of quantum technology and science communication, it is especially important to broaden the geographical scope of the research as quantum technology may deepen existing global inequalities when populations are denied access to the benefits that the technology can offer (Ten Holter et al., 2022).

It is thus important that the field of science communication and quantum technology is also understood from the perspective of the Global South, which future research should consequently focus on. For example, future research could, as a first step, determine whether and how national newspapers in Africa, Latin America and Asia are currently communicating about quantum science and technology to their readers.

6.5 Connecting quantum technology and society

A core motivation for conducting the research reported in this dissertation was to contribute to a better understanding of how information that is shared with non-expert audiences may contribute to creating a good connection between quantum technology and society. Based on the implications of this dissertation (section 6.3.1), we offer four recommendations for science communication researchers and four recommendations for science communicators:

Recommendations for science communication researchers

1. Empirically examine claims about potential issues, as only then true insight is gained into whether such potential issues are frequently presented to non-expert audiences.
2. Investigate the way potential issues appear across different types of public communication about quantum technology, such as books (Dihal, 2017), documentary films (Gaunkar et al., 2022), and games (Seskir et al., 2022), to determine whether the patterns in English TEDx talks and Dutch newspaper are a general trend.
3. Continue investigating how certain communication decisions about largely unfamiliar topics shape outcomes, in order to better understand which type of information influences which type of dependent variable for which audience segment(s) in the context of emergent technologies.
4. Extend framing studies beyond support to include other dimensions of engagement, in order to develop a deeper understanding of how communication influences public perceptions of emergent technologies.

<u>Recommendations for science communicators</u>

1. Decide for yourself whether or not to present quantum science as something spooky or enigmatic, as a brief, single mention seems to have no advantage or disadvantage to engagement.
2. Choose whether to explain counterintuitive quantum phenomena depending on your communication goal:
   (a) Explain a quantum phenomenon if your goal is to increase interest in, and engagement with, quantum technology, or if your goal is to (slightly) increase your audience's actual understanding of the phenomenon.
   (b) Do not explain a quantum phenomenon if your goal is to make your audience feel that they have understood your communication itself.
3. Decide for yourself whether to explain counterintuitive quantum phenomena using metaphors, as these do not seem to offer any additional advantage over non-metaphors. However, when using metaphors, be careful to ensure that they are not too complex or mysterious to convey, as otherwise they may lead to resistance from experts.

4. Pay attention to a broader range of quantum technologies and emphasize their potential benefits *and* risks, to ensure a balanced perspective.

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Appendix

A1 Appendix I

A1.1 Reasons for deleting transcripts in step 4 of the data collection

See Table A1.

A1.2 Low Krippendorff's α in Phase 2 for codes with low prevalence

In Phase 2 of the coding scheme, Krippendorff's α remained low for some of the codes while they achieved high percent agreements. Table A3 shows the number of times those codes appeared in talks (which we think might have been detrimental for α) together with the corresponding percentage agreement and α.

Table A3

The intercoder reliability for codes with a low prevalence in Phase 2.

Code in Phase 2	Percent agreement	$\alpha < .667$	Number of times coded in 15% of data after discussion (76 transcripts)
Laser	93%	0.63	4
Smartphone	84%	0.25	3
Computer	80%	0.40	6
Quantum sensor	96%	-0.13	1
Social progress	82%	0.38	6
Economic development / competitiveness	91%	0.32	4
Risk frame	91%	0.41	4
Contextuality explanation	92%	0.66	12

Table A1

Reasons for deleting transcripts in step 4 of the data collection.

Reasons for deleting a transcript in step 4	Example	Automatically transcribed	Manually transcribed
1. Used the keyword to metaphorically denote a sudden change or step forward	“quantum leap” “that was a quantum step up from zero”	69	12
2. Mentioned the keyword in a list of other types of sciences, technologies or other terms without any further mention of it	“But if I make a list – ok, chemtrails is a bit more extreme – zodiac signs, let’s see, tarot cards, quantum-psycho. . . ”	101	28
3. One or multiple persons or institutes are involved in or know about quantum science, but there is no mention of the keyword any further	"Quantum physicist Max Planck has said, ‘When you change the way you look at things, the things you look at change.’”	48	15
4. The speaker clarifies that s/he is not using/talking/going to talk about quantum science	“I just finished my PhD in September on the quantum photophysics of organic solar cells. That’s not what my talk is on, so don’t worry.” "I don’t mean that in the quantum mechanical sense of the term of parallel universe"	24	4
5. Mentioned the keyword to indicate something’s superiority / significance or a quantity of something	"One zettabyte is equal in to all the video titles on netflix x 470 million times. This is the quantum of data."	18	1
6. Using keyword to indicate that a topic is very difficult	"Then stop spending that much, save a little and buy yourself that new rifle. It’s not quantum physics!”	6	2
7. Due to another reason, which we indicated in our annotations	E.g. making a side joke: “You, as a non-quantum observer, (Laughter), can see this band...”	108	14

A1.3 The origins of the TEDx talks in our dataset

The TEDx talks have been presented at events that were held in 55 different countries. Figure A1 shows the percentage of TEDx talks per continent and Table A5 presents the top 10 countries that appear in our dataset most often.

Figure A1

The percentage of TEDx talks in our dataset for each continent.

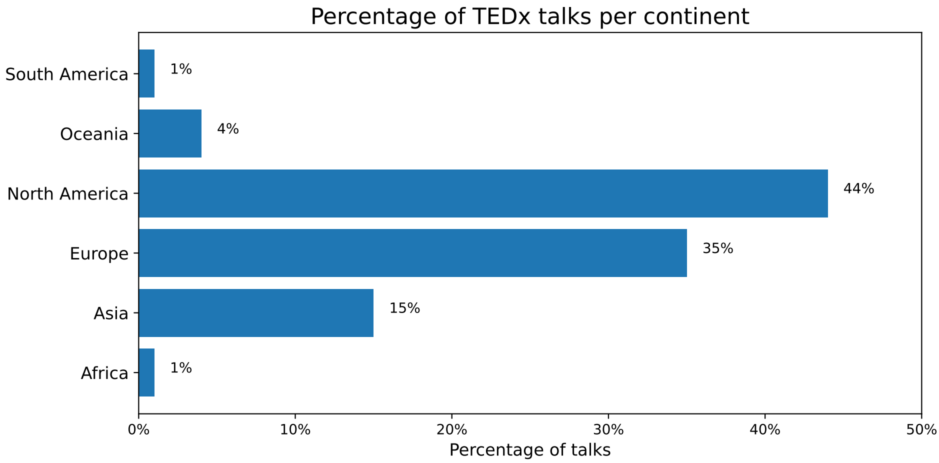


Table A5

Number of TEDx talks per country.

Country	Number of TEDx talks
United States	181
United Kingdom	46
Canada	37
India	37
Australia	20
Netherlands	18
Belgium	14
Germany	13
Italy	11
France	9

A1.4 Comparison between experts and non-experts

Figure A2

The benefits and risk frame for specific fields. These fields are based on Stichting Quantumdelta NL (2020) prediction of fields that will benefit from quantum 2.0 technology.

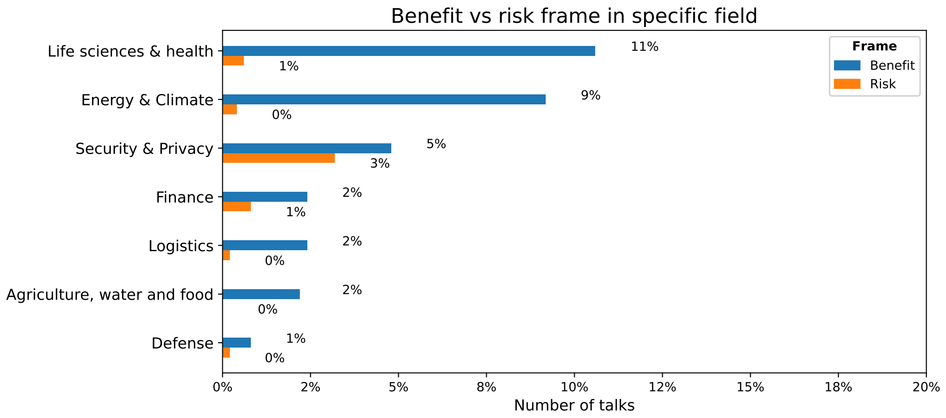
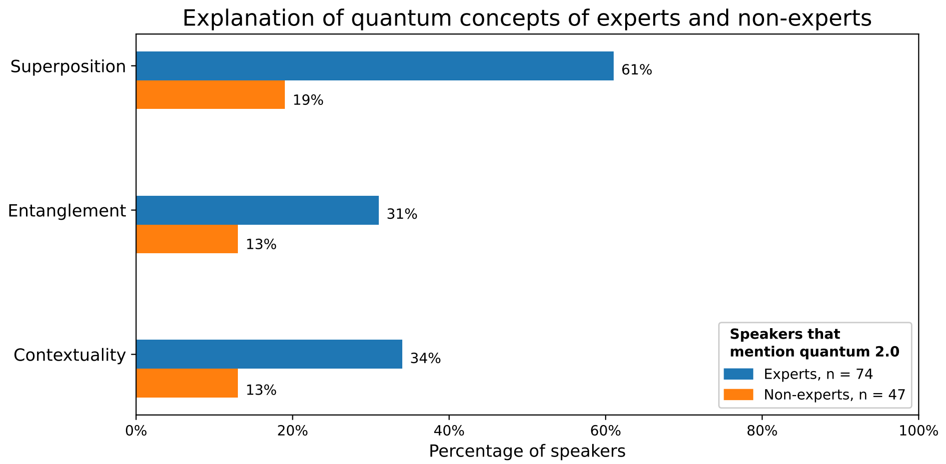


Figure A3

The percentage of speakers per expertise group that provide an explanation of an underlying quantum phenomenon when mentioning quantum 2.0 technology.



A1.5 The complete coding scheme

The complete coding scheme for Chapter 2 is presented in this section.
The complete coding scheme for Chapter 3 is very similar, but there are some differences in, for example, the identification part. It can be accessed via *this link*.

1. Identification

1. Who is coding?
   1 = Coder A, 2 = Coder B
2. What is the video ID of the TEDx talk?
3. What is the title of the TEDx talk?
   If no title is given, insert 0.
4. In what year was the TEDx talk published on the TEDx YouTube Channel?
5. What is the name of the TEDx event?
6. Is the transcription automatically generated?
   0 = no, 1 = yes
7. Is the TEDx talk flagged in the TEDx talk description? This means that it falls outside TEDx's curatorial guidelines.
   0 = no, 1 = yes

2. Speaker identification

8. What is the number of speakers in the TEDx talk?
   If there are 2 speakers, code 9 and 10 for each speaker separately.
9. What is the name of the speaker?
10. What is the quantum expertise and current profession of the speaker as provided in the YouTube description?

    Quantum experts are scientists (undergraduates and graduates excluded) and leaders (e.g. a founder, director, CEO, chairman, chief, etc.) at a university, institute, research initiative, start-up, or another organization working in or having worked in the field of quantum nanotechnology or another field in which quantum science plays a role. These include:

    - *Examples of fields in quantum nanotechnology: quantum technology, quantum information processing, quantum computational processing, nanotechnology*

- *Other examples of fields in which quantum science plays a role: quantum mechanics, quantum field theory, string theory, quantum optics, quantum cosmology (incl Big Bang theory and the black hole information paradox), quantum gravity, particle physics, high energy physics, photonics, condensed matter physics, nuclear physics, post-quantum cryptography*

If someone is described as a quantum expert: code 1 or 2.
If the quantum expertise is undefined, code 10.
If someone has no quantum expertise and multiple current professions apply: choose the first profession in the list or if other: code 11.

1 = quantum expert currently working at a university/research institute/(inter)national research organisation

Exclude (under)graduate students (=11). E.g. of an international research organisation: CERN, TNO.

2 = quantum expert currently working at a company or other/unknown

If other/unknown: specify the other/unknown in the 'comment' column. E.g. of other/unknown: a retired quantum expert, or a quantum physicist working at the EU Quantum Flagship (=international initiative).

3 = academic / leader at a university/research institute/(inter)national research organisation, main expertise domain lies outside quantum science.

Exclude (under)graduate students (=11), exclude leaders of spiritual institutes (=7)

4 = (executive) manager / leader at a company

Exclude quantum experts (=2), exclude founders of research institutes (=1 or 3) or other initiatives (=2, 7 or 11), like leaders of spiritual institutes (=7))

5 = high school teacher

Exclude university lecturers (=3)

6 = traditional medical health specialist working in health care

E.g. a surgeon, psychologist, psychiatrist

7 = alternative medical health specialist working in a holistic medical field or in a spiritual centre

E.g. a holistic doctor, sound therapist, founder of a spiritual centre

8 = high school student
9 = artist currently working in performing arts (e.g. musician) or in design (e.g. designer, architect)

Include artists that bridge quantum science and arts with each another.

10 = (quantum expertise) unknown

No information on the speaker is given or the quantum expertise is undefined. The latter means that the speaker works in a 'broad' field that includes both classical and quantum science and the specific research is not specified, e.g. 'a professor in physics' without a specification of the research s/he works on.
Examples of 'broad' fields are astrophysics, physics, cosmology - incl dark energy and black holes-, biology, chemistry.
When the current profession is known: include in comment section.

11 = other, namely...

E.g. an undergraduate or graduate student, a monk, an officer
Also code 11 if the profession only partly fits one of the non-quantum expert categories above, e.g. a biomedical engineer but it is unclear whether s/he works at a university or in a company.
If someone has multiple professions: choose the first one you come across in the talk.

3. Focus of the TEDx talks

11. Is a main topic of the TEDx talk 'quantum'?
0 = no
1 = yes, on quantum nanotechnology

The talk focusses on quantum science applications such as nanotechnology, quantum technology 1.0 (technology based on quantum transport) or quantum technology 2.0 (manipulating and reading out single quantum states, falls into one of the application domains: quantum computing & simulation, quantum communication, and quantum sensing & metrology).

2 = yes, on quantum science or a topic in which quantum science plays a role (exclude quantum nanotechnology)

The talk is about pure quantum science, or a topic in which quantum science plays a role. Examples are a talk on quantum mechanics, quantum field theory, string theory, quantum optics, quantum cosmology (incl Big Bang theory and the black hole information paradox), quantum gravity, particle physics, high energy physics, photonics, condensed matter physics, nuclear physics, post-quantum cryptography.

12. Does the TEDx talk include a holistic viewpoint?

    An example of a holistic viewpoint is when a speaker mentions that quantum mechanics tells us that everything is interconnected, for example that an illness in one causes an illness in others too.

    0 = no, 1 = yes

13. Is a quantum technology 2.0 indicator present in the transcript?

    Quantum technology 2.0 indicators include the term 'quantum' and belong to one of the following application domains: quantum computing & simulation, quantum communication, and/or quantum sensing & metrology.
    Examples: quantum technology, quantum computer, quantum algorithm.

    0 = no, 1 = yes

14. If a quantum technology 2.0 indicator is present (13 is 1=yes), quote the quantum technology 2.0 indicator. If multiple quantum technology indicators are present, only quote the first one.

Researching quantum science applications, frames and explanations

15. Is there at least one technology application of quantum science present in the transcript?

    Include: quantum technologies 1.0 (applications based on quantum physics such as the laser or smartphones), quantum technologies 2.0 (applications such as quantum computers and quantum networks), as well as other nanotechnologies (other applications in the nanometer-size range such as nanotubes).

    Do not include: when the transcript includes classical technologies based on quantum physics (i.e. quantum technologies 1.0), but the link with quantum physics is absent in the transcript.

    0 = no, 1 = yes

16. Quantum science applications: which technology application(s) of quantum science is/are mentioned?

    For each technology, indicate whether it is mentioned (0 = no, 1 = yes). Codes 1 to 5 are examples of quantum technology 1.0 and codes 6 to 8 of quantum technology 2.0.

    1 = Laser
    2 = MRI scanner

3 = Smartphone
4 = Computer
5 = Nuclear energy
6 = Quantum computer or quantum simulator
7 = Quantum network, quantum internet, quantum cryptography
8 = Quantum sensor
9 = Other / category unsure

Quantum science frames

17. Is the frame 'Quantum science (applications) is (are) spooky or enigmatic' present?

    Include: when a synonym of spooky or enigmatic refers to quantum science, a quantum science principle or a quantum science application. E.g.: quantum entanglement, quantum tunneling, string theory, quantum simulator.

    Do not include: when a synonym of spooky or enigmatic refers to concepts that follow the rules of quantum science, like photons and atoms, or that might be related to quantum science, like dark energy.

    0 = no, 1 = yes

18. If the spooky frame is present (17 is 1=yes), quote the sentence that includes the frame. If multiple sentences apply, only quote the first one.
19. Is the frame 'Quantum science (applications) lead(s) to social progress' present?

    Include: Quantum nanotechnologies could help solve societal problems (e.g. climate change and global malnutrition), or quantum nanotechnologies would impact society in a positive way.

    Do not include: If there is no mention of society being impacted, or if it is not clear whether society is impacted in a positive way (i.e. whether quantum nanotechnology brings social progress).
    For example: "Quantum nanotechnologies would change the lives of many": do not include if it does not becomes clear that the lives of many will change in a positive way.

    0 = no, 1 = yes

20. If the social progress frame is present (19 is 1=yes), quote the sentence that includes the frame. If multiple sentences apply, only quote the first one.
21. Is the frame 'economic development/competitiveness' present?
    The 'economic development/competitiveness frame' in relation to quantum science and its applications means that various parties are in competition to develop quantum nanotechnology, there is a quantum race going on. These parties invest heavily in quantum nanotechnologies. Quantum nanotechnology will provide economic growth, and will therefore have an impact on all kinds of industries.
    Note: both the social progress frame and the economic development frame can appear in a text: one frame does not exclude the other.

    > *For example: Nations should invest in quantum nanotechnologies in order to win the quantum race*

    0 = no, 1 = yes
22. If the economic development/competitiveness frame is present (21 is 1=yes), quote the sentence that includes the frame. If multiple sentences apply, only quote the first one.
23. Are benefits of quantum science (applications) mentioned?

    > *For example: quantum computers will be able to solve specific simulation and optimalisation problems exponentially faster than supercomputers currently can.*

    0 = no, 1 = yes
24. If benefits are mentioned (23 is 1=yes), quote the sentence that includes the benefit. If multiple sentences apply, only quote the first one.
25. If benefits are mentioned (23 is 1=yes): are specific fields to which the benefits apply mentioned?
    For each field, indicate whether it is mentioned (0 = no, 1 = yes).

    1 = Life sciences & health

    > *For example: using quantum simulators to develop new medicines.*

    2 = Finance

    > *For example: using quantum computers to run optimalisation algorithms to help model the risks of investment decisions.*

    3 = Logistics

    > *For example: using quantum computers to run optimalisation algorithms to model the traffic flow.*

    4 = Security & privacy

For example: data will be inherently safe against eavesdropping with the use of quantum networks.

5 = Defense

For example: using quantum sensors during military missions for navigational purposes (in case GPS cannot be used, for example in hostile environments or underground).

6 = Energy & climate

For example: using quantum computers to model better batteries.

7 = Agriculture, water and food

For example: using quantum sensors to detect water contamination.

8 = other

26. Are risks of quantum science (applications) mentioned?

    For example: quantum computers will impact the financial system, because cyber criminals can hack online banking; terrorists will be able to create new weapons by using a quantum computer; the power difference between poor and rich countries becomes bigger once the rich countries own quantum technologies whereas the poor do not.

    0 = no, 1 = yes

27. If risks are mentioned (26 is 1=yes), quote the sentence that includes the risk. If multiple sentences apply, only quote the first one.
28. If risks are mentioned (26 is 1=yes): are specific fields to which the risks apply mentioned?
    For each field, indicate whether it is mentioned (0 = no, 1 = yes).

    1 = Life sciences & health

    For example: terrorists using quantum simulators for bioterrorism purposes.

    2 = Finance

    For example: cyber criminals using quantum computers to hack into online banking.

    3 = Logistics

    For example: terrorists using quantum computers to get access to air and railroad traffic controls.

    4 = Security & privacy

    For example: governments losing their grip on criminal organizations that make use of quantum communication.

5 = Defense

For example: terrorists using quantum computers to gain access to military information.

6 = Energy & climate

For example: terrorists using quantum computers to hack into energy plants.

7 = Agriculture, water and food

For example: terrorists using quantum computers to hack into water supplies and water management.

8 = other

Quantum science explanations

29. Is the word 'superposition' mentioned?
0 = no, 1 = yes

30. Is an explanation provided of the quantum science principle: superposition?

A particle in a superposition state can be in multiple quantum states at the same time. For example, when an electron is in a superposition state, it can exist in spin states up and down at the same time.

Include: something is 0 and 1 at the same time.

Do not include: when there is no explanation present, but the speaker just mentions the word 'superposition'. For example: a qubit can be in a superposition of 0 and 1.

0 = no, 1 = yes

31. If an explanation of superposition is provided (29 is 1=yes), quote the sentence that includes the explanation. If multiple sentences apply, only quote the first one.

32. Is the word 'entanglement' mentioned?
0 = no, 1 = yes

33. Is an explanation provided of the quantum science principle: entanglement?

Two entangled particles share an extremely strong connection with each other - measuring one of the particles instantly affects the state of the other, even when the particles are separated by a large distance. In other words: entangled particles can only be described by the quantum state for the entire system, and not by their individual quantum states.

Include: two entangled particles affect each other even when they are very far apart. Also include if an analogy or metaphor is provided to explain the principle.

Do not include: holistic explanations like everything is interconnected.

0 = no, 1 = yes

34. If an explanation of entanglement is provided (32 is 1=yes), quote the sentence that includes the explanation. If multiple sentences apply, only quote the first one.

35. Is an explanation provided of the quantum science principle: contextuality?

    Contextuality means that "outcomes of measurements [depend] on other measurements on the self same system" (G. Jaeger, 2019, p 2). This is operationalised as that when one performs a measurement on a quantum state, that measurement affects the quantum state irreversibly.

    Include: a measurement or observation affects the state of a quantum system

    Do not include: when there is no mention of measurement / observation (e.g. when complementarity is mentioned but without any mention of contextuality.)

    0 = no, 1 = yes

36. If an explanation of contextuality is provided (35 is 1=yes), quote the sentence that includes the explanation. If multiple sentences apply, only quote the first one.

A2 Appendix II

A2.1 The hybrid automatic-manual process to detect duplicates

To detect duplicates, we used a hybrid automatic-manual process. We defined two articles as duplicates if they were: 1) perfect 1-to-1 copies, 2) a basic version vs. an extended/edited version, 3) a preview vs. the main article, or 4) copies of articles with small changes in individual words or clauses (i.e., not a perfect 1-to-1 copy, but articles with equal content and matching sentences for most words).

For articles to be duplicates, the overlap had thus to be at least one whole paragraph (single matching sentences were not sufficient). Exceptions to this were if two articles shared 1-to-1 paragraphs but both had at least one exclusive paragraph, we kept both in. Also, if two articles were duplicates, but they were published on dates 3 or more months apart, we kept both because to readers these articles could appear to be independent of each other and consequently result in a double salience of the topic. Also, the context and relevance of a similar article published on different dates may change over time, so that a later republished article may be perceived differently than on its original publication date. If agency reports are stretched/extended by a newspaper editor, they were also not marked as duplicates since they might contain unique content for the newspaper brand. Finally, articles that were highly similar in length and content and for which most sentences had been paraphrased were both kept in, as paraphrasing could have affected the frames.

To make sure that we detected all types of duplicates, we wrote a script that automatically evaluates the similarity of articles based on both edit- & overlap-distances to cover all the various duplicate types (we used the following similarity metrics: Damerau-Levenshtein Distance, Ratcliff/Obershelp “Distance”, Overlap “Distance”). The articles that our script identified as very similar were checked manually. In order to prevent missing duplicates, we chose this minimum value to be on the low side relative to the typical similarity scores that we found for duplicates in 2009 and 2021. As a consequence, the second author still checked hundreds of article pairs manually, but this number was much lower than if we would have performed a full manual duplicate check. Articles were removed from our dataset if they met our definition of a duplicate article. Perfect 1-to-1 copies and articles with small changes in individual words or clauses merely occurred 1) for articles with related brands (e.g. NRC.NEXT and NRC, which we merged into the single code NRC); and 2) for articles from the same news brand but published on different dates (<3 months apart). In the first case, the article from the main brand (e.g. NRC) was kept in the dataset, and for the second case, the article with the latest publication date was kept in. For basic versions vs. extended/edited edition and for a preview vs. the main article, the article with the most words was kept in the dataset.

Further technical details about the automated part of this process can be found in the scripts and accompanying instructions of our code repo: https://github.com/t-rothe/quantum-in-Dutch-newspapers.

A2.2 Reasons for discarding newspaper articles as irrelevant or unsuitable for the analysis

Table A7

Total number of articles discarded from the 2,240 unique articles.

Reasons for deleting an article	Example	Total Excluded
1. Keyword "quantum" contained in (common) terms unrelated to quantum science / technology, e.g. "quantum leap", "quantum grey", a 'quantum' as in a quantity of something	"The latest campaign cleverly responds to previous quantum leaps: 'The strippenkaart became the OV-chipkaart.'"	141
2. Keyword "Quantum" used in a proper noun that is unrelated to (quantum) science / technology, e.g. a company name or product name	"Quantum of Solace" [movie] "He added that the Dutch occupants were in a Quantum-minivan belonging to tour company Eco Coaches."	599
3. Metaphorically referring to quantum (concepts) to make a point / explain something else, i.e. without further notice or explanation of (quantum) science / technology.	"Quantum mechanics states that light is a wave and a particle at the same time. [...] And now I'm actually proposing something similar where people are concerned. Can you experience another person as a fellow human being and as a stranger at the same time?"	35
4. Mentioned a word/proper noun containing the keyword "Quantum" as part of a text/document that only forms a: TV guide, table of contents for (news) articles, (event) announcements, short independent corrections on earlier articles (e.g. misspellings), or other short listings of independent and incoherent sentences / words	"SUN 5 APR Search for the lowest temperature and visible quantum phenomena. Lecture by physicist Dirk Bouwmeester."	74
5. Mentioning / Listing quantum science (concepts), technology as a scientific or technological example without further mention, explanation or discussion of the topic.	"... for example an LED, or another light source like a quantum well."	223

Reasons for deleting an article	Example	Total Excluded
6. Mentioning scientific instruments / experiments or names of other things with the keyword "Quantum" without mentioning or discussing its relation to quantum science (concepts) or technology	"The rocket carried the so-called X-Ray Quantum Calorimeter ..."	54
7. Used the topic or a concept of quantum physics / technology as an example to make a point or explain something else, i.e. without further notice of (quantum) science / technology.	"If you also want to describe what happens inside molecules, you have to do quantum mechanical calculations. But then you get nowhere - then you can only describe a hydrogen atom."	241
8. Mentioning or listing a person or institution that is related to / works on / knows about quantum science or technology without further mention or discussion of the topic itself.	"The science battle between quantum scientist Julia Cramer and cognitive neuroscientist Barbara Braams: it will be spectacular."	109
9. Mentioning the topic of quantum science (concepts) or technology to indicate that something unrelated is (not) difficult / (not) complex (to understand). OR Indicating that the author/someone else does not understand quantum science / technology.	"Now Kleine Goos knows as much about the [Sacred] Scripture as about quantum mechanics, ..."	33
10. Very shortly mentioning quantum physics in relation to paranormal, consciousness, reality without any explanation of the quantum physics part	"I wonder if there is something of his inner world left in his skull, an energetic quantum-like something, in a matter that I cannot observe."	33

Note. The quotes have been translated from Dutch.

A2.3 Data of the sample

Table A8

Frequency table of the descriptives of the sample

		n	%	95% CI
Authors	Unique	117		
	Missing	60		
Number of articles	NRC	147	38.2%	[0.333, 0.430]
	De Volkskrant	130	33.8%	[0.290, 0.385]
	Trouw	54	14.0%	[0.106, 0.175]
	Algemeen Dagblad	12	3.1%	[0.014, 0.049][a]
	De Telegraaf	27	7.0%	[0.045, 0.096]
	Het Parool	15	3.9%	[0.020, 0.058]
Article type	News reports and features	234	60.8%	[0.559, 0.657]
	Opinion pieces, columns or letters	60	15.6%	[0.120, 0.192]
	Reviews of a product or announcements of upcoming events	51	13.2%	[0.099, 0.166]
	Interviews	40	10.4%	[0.073, 0.134]
Most popular	*Section:* Science	176	45.7%	[0.407, 0.507]
	Day: Saturday	215	55.8%	[0.509, 0.608]

Note. [a]indicates the exact Clopper–Pearson confidence interval was calculated.

A2.4 Intercoder reliability results

Table A10

Intercoder reliability results after coding round 3 (n = 78 articles) for the different codes that are categorised under descriptives, barriers, effective and prominent. The codes with a low agreement (Krippendorff's α < .667) are marked in red. The number of times '1' is coded is counted after the discussion. Agr. = agreement.

		#'1' coded	α	% agr.
Descriptives	Article type		0.78	88.5%
	Main focus		0.62	75.6%
	Quantum technology indicator	37	0.95	97.4%
	Quantum computing & simulation	32	0.91	97.4%
	Quantum communication	7	0.69	92.1%
	Quantum sensing & metrology	0		100%
Barriers	Spooky and enigmatic	19	0.83	93.6%
	Economic development / competitiveness	10	0.77	94.9%
	Superposition explanation	18	0.86	94.9%
	Entanglement explanation	8	1.0	100%
	Contextuality explanation	7	0.75	96.2%
	Mystical	2	0.66	98.7%
Effective	Social progress	5	0.74	97.4%
	Benefit	29	0.89	94.9%
	Risk	7	0.84	97.4%
Prominent	Spooky and enigmatic	8	0.54	80.0%
	Economic development / competitiveness	3	0.73	87.5%
	Social progress	1		100%
	Benefit	8	0.81	92.3%
	Risk	2	1.0	100%

Note. The results section also contains an analysis of the quantum science explanation prominence and mystical viewpoint prominence code. This analysis was done based on a written discussion between the first and second coder.

A2.5 Analysis plan

The analysis involved calculating the number of times *n* a code occurred, its sample proportion *p* and its confidence interval. As we drew a probability sample of 385 articles, these confidence intervals were 95% confidence intervals with a 5% margin of error, meaning we have a 95% confidence that the true population proportion is within 5% of the sample proportion. Before calculating the confidence intervals, we first checked the assumption of at least 15 occurrences and 15 non-occurrences of a code such that $mp \geq 15$ and $m(1-p) \geq 15$, where m is the sample size and p is the sample proportion ('Basic Statistics', n.d.). If the assumption was not met, we calculated the exact Clopper-Pearson confidence interval instead (indicated with a [a] in the Results section), which is a more conservative measure ('Epitools - Calculate confidence limits for a sample prop ...' n.d.).

A2.6 Prominence of frames in news reports and features

Table A12

Frequency table of the prominent themes in news reports and features (n = 234). The percentage given is with respect to the total number of prominent themes (n = 61).

Frame	Total number of times the frame is prominent	Percentage compared to total number of prominent frames (*n* = 61)	95% CI
Spooky and enigmatic	15	24.6%	[0.138, 0.354]
Economic development / competitiveness	6	9.8%	[0.037, 0.202][a]
quantum phenomenon explanations for articles with quantum technology indicator (*n* = 132)	11	18.0	[0.094, 0.300][a]
Mystical viewpoint	2	3.3%	[0.004, 0.114][a]
Social progress	1	1.6%	[0.000, 0.088][a]
Benefit	25	41.0%	[0.286, 0.533]
Risk	3	4.9%	[0.010, 0.137]

Note. Multiple prominent frames can occur in one article. In total, 49 articles put at least one of the frames in a prominent position. [a]indicates the exact Clopper–Pearson confidence interval was calculated.

A2.7 Additional figures

Figure A4

Number of articles by year of publication in total dataset (N = 698).

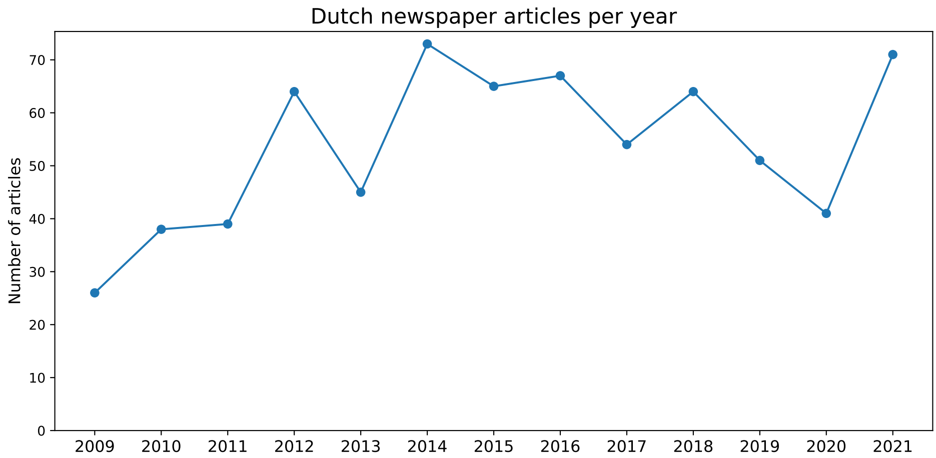


Figure A5

Number of articles by year of publication per newspaper brand (N = 385).

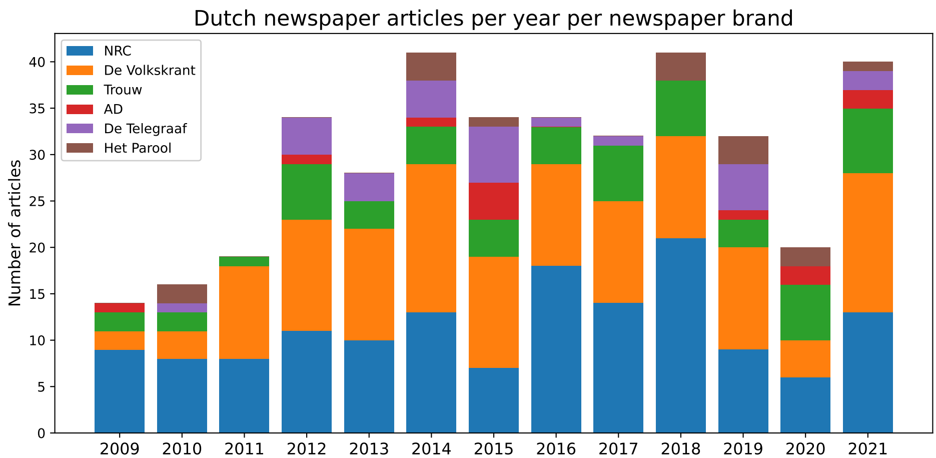


Figure A6

The percentage of articles that explain superposition, entanglement or contextuality when referring to quantum technology. The error bars are based on the sampling.

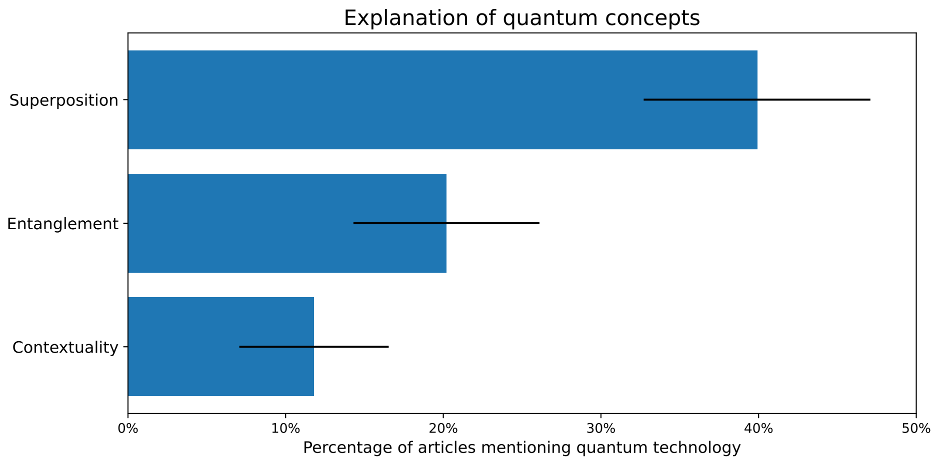
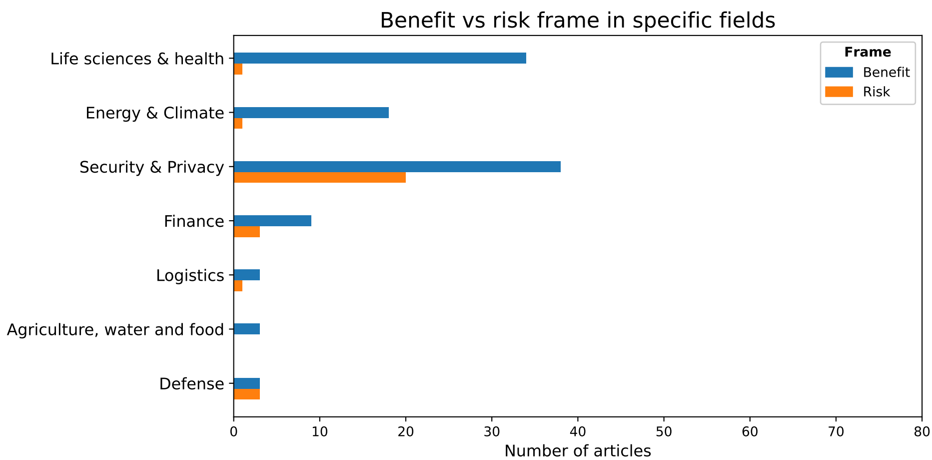


Figure A7

Number of times a specific field was mentioned in terms of benefits and risks.



A3 Appendix III

A3.1 Rationale for the 2 x 2 x 4 between-subjects design

In this study, we opted for a 2 (enigmatic, not enigmatic) x 2 (explanation, no explanation) x 4 (none, benefit, risk, balanced) between-subjects design. This is opposed to a simpler approach that might include only separate conditions for an enigmatic frame, an explanation frame, a benefit frame, a risk frame, a balanced frame, and a control condition. There are two reasons for our 2x2x4 design:

(a) A 2x2x4 design answers our research questions better.

A 2x2x4 design answers our research questions more precisely than a simpler approach. To clarify this, we focus first on the simplified 2 (enigmatic, not enigmatic: A = 0 or 1) x 2 (explanation, no explanation: B = 0 or 1) design. The extension to the third dimension is conceptually obvious.
In the 2x2 design, there are four conditions possible:

	No explanation (B = 0)	Explanation (B = 1)
Not enigmatic (A = 0)	(a)	(b)
Enigmatic (A = 1)	(c)	(d)

The simpler design would involve a control group that is similar per test: one for the effect of providing an explanation (comparison of (a) with (b)) and one for the effect of an enigmatic frame (comparison of (a) and (c)). It does not include (d). In our 2x2x4 design, we can investigate whether the effect of A differs based on the presence or absence of B – something we cannot when we would have used the simpler design. We are thus able to compare the average scores across conditions (for example, the effect of A is measured by comparing ((a)+(b))/2 with ((c)+(d))/2), and therefore we get a better picture of the general pattern. The 2x2x4 design thus answers the research questions better.

(a) A 2x2x4 design is more efficient.

In addition to better addressing our research questions, a 2x2x4 design is also more efficient as opposed to such a simpler design. Suppose a power analysis indicates that 50 participants are needed per group. In the simpler design, this requires a total of 150 participants: 50 in the control group (a), 50 in the experimental group (b) and 50 in the experimental group (c).

In a 2x2x4 design, only 100 participants are needed: 25 for (a) to (d) each. For example, when evaluating the effect of the enigmatic frame (A), we combine conditions (a) and (b) and compare them with conditions (c) and (d), allowing a comparison of 50 with 50 participants. The approach therefore either requires fewer participants or increases statistical power, making the design more efficient.

Table A15

Wordings for the 16 experimental conditions

Nr	Group	Wordings for Experimental Conditions (in Dutch)	Wordings for Experimental Conditions (translated to English)
1	Control group	Control group statement: "Quantumtechnologie is een opkomende technologie. Quantumtechnologie gebruikt wetenschappelijke kennis die de allerkleinste deeltjes beschrijft, zoals elektronen."	Control group statement: "Quantum technology is an emerging technology. Quantum technology uses scientific knowledge that describes the smallest particles, such as electrons."
2	Enigmatic frame group	Enigmatic frame statement: "Quantumtechnologie is een opkomende technologie. Quantumtechnologie gebruikt wetenschappelijke kennis die de allerkleinste deeltjes, zoals elektronen, op een raadselachtige manier beschrijft."	Enigmatic frame statement: "Quantum technology is an emerging technology. Quantum technology uses scientific knowledge that describes the smallest particles, such as electrons, in a mysterious way."
3	Explanation of a quantum phenomenon group	Control group statement + One of the following 6 statements (Explanation frame statement):	Control group statement + One of the following 6 statements (Explanation frame statement):
	1a) Superposition - definition	1a) "Zo zegt deze wetenschap dat het voor kleine deeltjes mogelijk is om op twee plaatsen tegelijkertijd te zijn. Dit is iets dat we in ons dagelijks leven niet zien. In ons dagelijks leven kan iets maar op één plek tegelijkertijd zijn."	1a) "For example, this science says that it is possible for small particles to be in two places at the same time. This is something that we don't see in our daily lives. In our daily lives, something can only be in one place at the time."
	1b) Superposition - analogy	1b) "Zo zegt deze wetenschap dat het voor kleine deeltjes mogelijk is om op twee plaatsen tegelijkertijd te zijn. Stel dat dit ook voor een auto zou gelden. Dan zou een auto op twee verschillende wegen tegelijk kunnen rijden, bijvoorbeeld op de A2 en tegelijkertijd op de A28. Dit is iets dat we in ons dagelijks leven niet zien. In ons dagelijks leven rijdt een auto óf op de A2 óf op de A28."	1b) "For example, this science says that it is possible for small particles to be in two places at the same time. Suppose this also applies to a car. Then a car could drive on two different roads at the same time, for example on the A2 and at the same time on the A28. This is something we don't see in our daily lives. In our daily lives, a car either drives on the A2 or the A28."

Nr	Group	Wordings for Experimental Conditions (in Dutch)	Wordings for Experimental Conditions (translated to English)
	2a) Entanglement - definition	2a) "Zo zegt deze wetenschap dat twee kleine deeltjes die ver weg zijn, toch sterk met elkaar verbonden zijn. Als de toestand van het ene deeltje verandert, verandert de toestand van het andere deeltje onmiddellijk mee. Dit is iets wat we in ons dagelijks leven niet zien."	2a) "For example, this science says that two small particles that are far away are still strongly connected. If the state of one particle changes, the state of the other particle changes immediately. This is something we don't see in our daily lives."
	2b) Entanglement - analogy	2b) "Zo zegt deze wetenschap dat twee kleine deeltjes in een gezamenlijke toestand kunnen zijn. Daardoor heeft het geen zin meer om over deze twee deeltjes te praten alsof het twee afzonderlijke deeltjes zijn. Stel dat dit ook voor twee gekleurde ballen zou gelden. Als de ballen in een gezamenlijke toestand zijn en je kijkt naar de kleur van één bal, dan kan dat onmiddellijk de kleur van de andere bal beïnvloeden. Ook al is die andere bal mijlenver weg."	2b) "For example, this science says that two small particles can be in a joint state. As a result, it no longer makes sense to talk about these two particles as if they were two separate particles. Suppose this also applies to two coloured balls. If the balls are in a joint state and you look at the colour of one ball, it can immediately affect the colour of the other ball. Even though the other ball is miles away."
	3a) Contextuality - definition	3a) "Zo zegt deze wetenschap dat door naar een deeltje te kijken, de eigenschappen van dat deeltje kunnen veranderen. Dit is iets wat we in ons dagelijks leven niet ervaren. In ons dagelijkse leven verandert iets niet van eigenschap, zoals van kleur of vorm, alleen maar door ernaar te kijken."	3a) "For example, this science says that by looking at a particle, the properties of that particle can change. This is something we do not experience in our daily lives. In our daily lives, something does not change its properties, such as colour or shape, just by looking at it."
	3b) Contextuality - analogy	3b) "Zo zegt deze wetenschap dat door naar een deeltje te kijken, de eigenschappen van dat deeltje kunnen veranderen. Stel dat dit ook voor een trui zou gelden: zodra u naar de trui kijkt is deze bijvoorbeeld groen. Als u wegkijkt, en een stuk later opnieuw naar de trui kijkt, is de trui opeens grijs. Het kijken naar de trui heeft een fysiek effect op die trui."	3b) "For example, this science says that by looking at a particle, the properties of that particle can change. Suppose this also applies to a sweater: as soon as you look at the sweater it is for example green. If you look away and look at the sweater again a little later, the sweater is suddenly grey. Looking at the sweater has a physical effect on that sweater."

Nr	Group	Wordings for Experimental Conditions (in Dutch)	Wordings for Experimental Conditions (translated to English)
4	Benefit frame group	Control group statement + Benefit frame statement: "Sommige wetenschappers zeggen dat quantumtechnologie in de toekomst levens kan gaan redden of verlengen. Volledig ontwikkelde quantumtechnologie heeft namelijk de potentie om nieuwe medicijnen te ontwerpen."	Control group statement + Benefit frame statement: "Some scientists say that quantum technology could save or extend lives in the future. Fully developed quantum technology has the potential to design new medicines."
5	Risk frame group	Control group statement + Risk frame statement: "Sommige wetenschappers zeggen dat quantumtechnologie in de toekomst veiligheidsproblemen kan gaan veroorzaken. Volledig ontwikkelde quantumtechnologie heeft namelijk de potentie om gebruikt te worden voor cyberoorlogsvoering."	Control group statement + Risk frame statement: "Some scientists say that quantum technology could cause safety problems in the future. Fully developed quantum technology has the potential to be used for cyber warfare."
6	Balanced frame group	Control group statement + Balanced frame statement: "Sommige wetenschappers zeggen dat quantumtechnologie in de toekomst levens kan gaan redden of verlengen. Volledig ontwikkelde quantumtechnologie heeft namelijk de potentie om nieuwe medicijnen te ontwerpen. Andere wetenschappers zeggen dat quantumtechnologie in de toekomst veiligheidsproblemen kan gaan veroorzaken. Volledig ontwikkelde quantumtechnologie heeft namelijk de potentie om gebruikt te worden voor cyberoorlogsvoering."	Control group statement + Balanced frame statement: "Some scientists say that quantum technology could save or extend lives in the future. Fully developed quantum technology has the potential to design new medicines. Other scientists say that quantum technology could cause safety problems in the future. Fully developed quantum technology has the potential to be used for cyber warfare."
7	Enigmatic frame + Explanation of a quantum phenomenon group	Enigmatic frame statement + Explanation of a quantum phenomenon statement	Enigmatic frame statement + Explanation of a quantum phenomenon statement
8	Enigmatic frame + Benefit frame group	Enigmatic frame statement + Benefit frame statement	Enigmatic frame statement + Benefit frame statement
9	Enigmatic frame + Risk frame group	Enigmatic frame statement + Risk frame statement	Enigmatic frame statement + Risk frame statement
10	Enigmatic frame + Balanced frame group	Enigmatic frame statement + Balanced frame statement	Enigmatic frame statement + Balanced frame statement

Nr	Group	Wordings for Experimental Conditions (in Dutch)	Wordings for Experimental Conditions (translated to English)
11	Explanation of a quantum phenomenon + Benefit frame group	Control group statement + Explanation of a quantum phenomenon statement + Benefit frame statement	Control group statement + Explanation of a quantum phenomenon statement + Benefit frame statement
12	Explanation of a quantum phenomenon + Risk frame group	Control group statement + Explanation of a quantum phenomenon statement + Risk frame statement	Control group statement + Explanation of a quantum phenomenon statement + Risk frame statement
13	Explanation of a quantum phenomenon + Balanced frame group	Control group statement + Explanation of a quantum phenomenon statement + Balanced frame statement	Control group statement + Explanation of a quantum phenomenon statement + Balanced frame statement
14	Enigmatic frame + Explanation of a quantum phenomenon + Benefit frame group	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Benefit frame statement	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Benefit frame statement
15	Enigmatic frame + Explanation of a quantum phenomenon + Risk frame group	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Risk frame statement	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Risk frame statement
16	Enigmatic frame + Explanation of a quantum phenomenon + Balanced frame group	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Balanced frame statement	Enigmatic frame statement + Explanation of a quantum phenomenon statement + Balanced frame statement

Table A16

Engagement questions

Outcome variable	Cronbach's α	Statements (in Dutch)	Statements (translated to English)
Information seeking	3-item scale; α = 0.94	1. Ik ben van plan om binnenkort informatie over quantumtechnologie op te zoeken 2. Ik zal proberen om in de komende tijd informatie over quantumtechnologie op te zoeken 3. Het is mijn bedoeling om meer te weten te komen over quantumtechnologie	1. I plan to seek information about quantum technology in the near future 2. I will try to seek information about quantum technology in the near future 3. I intend to find out more information about quantum technology
Internal efficacy	4-item scale; α = 0.859	1. Ik denk dat ik goed in staat ben om deel te nemen aan discussies over quantumtechnologie 2. Ik heb het gevoel dat ik een redelijk goed begrip heb van de belangrijke kwesties rond quantumtechnologie waarmee Nederland wordt geconfronteerd 3. Ik heb het gevoel dat ik net zo goed een oordeel kan leveren op het gebied van quantumtechnologie als de meeste andere mensen 4. Ik denk dat ik beter geïnformeerd ben over quantumtechnologie dan de meeste mensen	1. I consider myself to be well qualified to participate in discussions about quantum technology 2. I feel that I have a pretty good understanding of the important quantum technology issues facing the country 3. I feel that I could do as good a job in the quantum technology field as most other people 4. I think that I am better informed about quantum technology than most people

Outcome variable	Cronbach's α	Statements (in Dutch)	Statements (translated to English)
General interest	6-item scale; α = 0.892	1. Ik wil meer leren over quantumtechnologie 2. Ik vind het debat rond quantumtechnologie interessant 3. Ik wil mij gaan verdiepen in quantumtechnologie 4. Ik ben nieuwsgierig geworden naar quantumtechnologie 5. Ik vind quantumtechnologie saai (reverse-coded) 6. Wat ik net heb gelezen over quantumtechnologie levert stof tot nadenken	1. I am interested in learning about quantum technology 2. I find the debate surrounding quantum technology interesting 3. I want to learn more about quantum technology 4. Quantum technology is exciting 5. I find quantum technology boring (reverse-coded) 6. These quantum technological ideas were thought-provoking
Perceived knowledge	4-item scale; We worked with items 1, 2 and 4 resulting in α = 0.848	1. Ik heb kennis over quantumtechnologie 2. Ik voel me goed geïnformeerd over zaken rond quantumtechnologie 3. Ik weet niet zoveel als ik zou willen weten over zaken rond quantumtechnologie (reverse-coded) 4. Ik heb vertrouwen in mijn begrip rond quantumtechnologie	1. I am knowledgeable about quantum technology 2. I am well-informed about issues related to quantum technology 3. I don't know as much as I'd like to know about the issues surrounding quantum technology (reverse-coded) 4. I trust my knowledge about quantum technology

A4 Appendix IV

A4.1 Text of stimulus material and different conditions

Participants were assigned to read a newspaper article about quantum containing either a metaphorical or non-metaphorical explanation of superposition or entanglement or no explanation at all. The original Dutch version and the English version, translated with the help of Google Translate and checked by all authors, are found below.

Original Dutch version

Nieuwe quantumcomputer voor Nederland

Nederland krijgt een van de acht nieuwe quantumcomputers die de Europese Commissie laat bouwen. Hiermee hopen ze Europa een betere concurrentiepositie te geven op het gebied van quantumtechnologie.

23 Oktober 2024

De Nederlandse quantumcomputer kost 20 miljoen euro. Hij komt op het Amsterdam Science Park en wordt naar verwachting in de zomer van 2026 gebouwd. Quantumcomputers werken anders dan de computers die we nu gebruiken. Ze maken gebruik van de principes van de quantumfysica, een domein binnen de natuurkunde dat zich bezighoudt met de allerkleinste deeltjes. Een belangrijk kenmerk daarin is *superpositie/verstrengeling*. Quantumcomputers maken onder andere gebruik van *superpositie/verstrengeling*, waardoor ze in de toekomst mogelijk bepaalde problemen sneller kunnen oplossen dan onze huidige computers.

	Item: Superpositie	*Item: Verstrengeling*
Conditie: Control	*No text.* (0 words)	*No text.* (0 words)
Conditie: Niet-metaforisch	Superpositie is een quantumfenomeen. Een deeltje in superpositie bevindt zich niet slechts in één toestand. Zolang het deeltje in superpositie is, is het in een combinatie van verschillende toestanden tegelijkertijd. Deze situatie blijft bestaan totdat we het deeltje meten. Pas als we een meting aan het deeltje doen komt het deeltje in één toestand. Deeltjes in de quantumwereld kunnen dus tegelijkertijd in meerdere toestanden bestaan totdat ze worden gemeten of waargenomen. Zo werkt het in de quantumwereld. (77 words)	Verstrengeling is een quantumfenomeen. Als twee deeltjes verstrengeld zijn, betekent dit dat hun toestanden op een bepaalde manier met elkaar verbonden zijn. Als je de toestand van het ene deeltje meet, weet je direct wat de toestand van het andere deeltje is. Zelfs als die deeltjes zich aan weerszijden van het universum bevinden. De toestand van het ene deeltje zorgt er dus voor dat de toestand van het deeltje waarmee het verstrengeld is vastligt. Zo werkt het in de quantumwereld. (80 words)
Conditie: Metaforisch	Superpositie is een quantumfenomeen. Een deeltje in superpositie kun je vergelijken met een muntje dat in de lucht draait. Zolang het muntje draait lijkt het alsof het tegelijkertijd kop en munt is. Deze situatie blijft bestaan totdat we de munt op tafel slaan. Pas als we de munt op tafel slaan komt het muntje op kop óf munt terecht. Het muntje lijkt dus tegelijkertijd kop én munt totdat het wordt gemeten of waargenomen. Zo werkt het in de quantumwereld. (79 words)	Verstrengeling is een quantumfenomeen. Verstrengelde deeltjes kun je vergelijken met een paar dobbelstenen waarbij de uitkomsten altijd hetzelfde zijn. Wanneer de ene dobbelsteen wordt gegooid, is de uitkomst van de andere dobbelsteen direct bepaald. Zelfs als deze aan de andere kant van de speeltafel wordt gegooid. De uitkomst van de ene dobbelsteen zorgt er dus voor dat de uitkomst van de dobbelsteen waarmee die verbonden is vastligt. Zo werkt het in de quantumwereld. (73 words)

De komst van een quantumcomputer is een belangrijk moment voor de concurrentiepositie van Nederland in quantumtechnologie. Maar wat de technologie precies voor jou en mij gaat betekenen is nog onduidelijk. De betrokken onderzoekers hopen hier met dit project meer over te weten te komen.

Translated English version

New quantum computer for the Netherlands

The Netherlands will receive one of eight new quantum computers that the European Commission is having built. They hope that this will give Europe a better competitive position in the field of quantum technology.

23 October 2024

The Dutch quantum computer costs 20 million euros. It will be located at the Amsterdam Science Park and is expected to be built in the summer of 2026. Quantum computers work differently than the computers we use now. They use the principles of quantum physics, a domain within physics that deals with the smallest particles. An important characteristic of this is *superposition/entanglement*. Quantum computers use *superposition/entanglement*, among other things, as a result of which, in the future, they may be able to solve certain problems faster than our current computers can.

	Item: Superposition	*Item: Entanglement*
Condition: Control	*No text.* (0 words)	*No text.* (0 words)
Condition: Non-metaphorical	Superposition is a quantum phenomenon. A particle in superposition is not just in one state. As long as the particle is in superposition, it is in a combination of different states at the same time. This situation continues until we measure the particle. Only when we perform a measurement on the particle does the particle enter a single state. Particles in the quantum world can therefore exist in multiple states at the same time until they are measured or observed. This is how the quantum world works.	Entanglement is a quantum phenomenon. When two particles are entangled, it means that their states are somehow connected. If you measure the state of one particle, you immediately know what the state of the other particle is. Even if those particles are on opposite sides of the universe. So the state of one particle ensures that the state of the particle it is entangled with is fixed. This is how the quantum world works.
Condition: Metaphorical	Superposition is a quantum phenomenon. A particle in superposition can be compared to a coin spinning in the air. As long as the coin is spinning, it appears to be heads and tails at the same time. This situation continues until we slap the coin on the table. Only when we slap the coin on the table does the coin land on either heads or tails. The coin therefore appears to be heads and tails at the same time until it is measured or observed. That is how it works in the quantum world.	Entanglement is a quantum phenomenon. Entangled particles can be compared to a pair of dice where the outcomes are always the same. When one die is thrown, the outcome of the other die is immediately determined. Even if it is thrown on the other side of the gaming table. The outcome of one die therefore ensures that the outcome of the die it is connected to is fixed. That is how it works in the quantum world.

The arrival of a quantum computer is an important moment for the competitive position of the Netherlands in quantum technology. But what the technology will mean exactly for you and me is still unclear. The researchers involved hope to find out more about this with this project.

A4.2 Intercoder reliability on actual comprehension

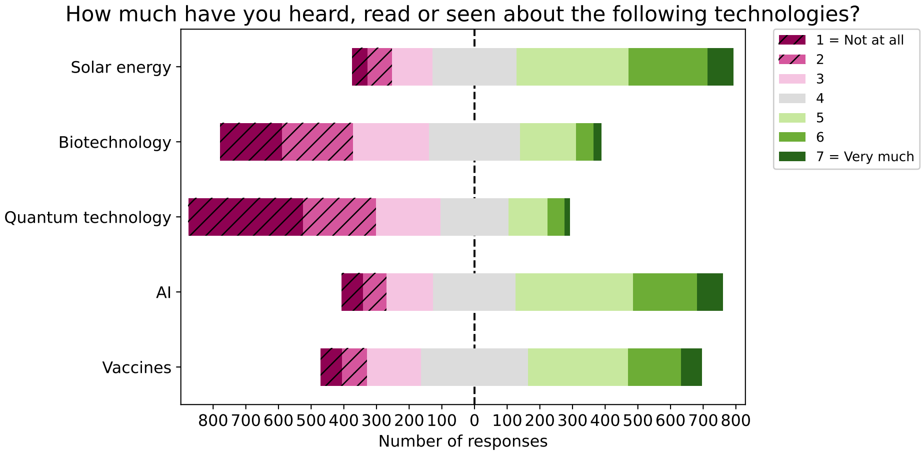
To ensure the reliability of the results on actual comprehension, two coders discussed the first 50 answers and rated the answers together. The two coders agreed in all cases and afterwards independently coded a sample of 10% of the answers (n = 117) to calculate intercoder agreement. We found perfect to near-perfect agreement between the coders for superposition and entanglement with α values between 0.86 and 1 (percent agreements between 96% - 100%), except for 2) there is a connection/correlation (α = 0.54, 84%). We modified this code slightly by specifying that using a synonym of connection/correlation, such as cooperation or fusion, would also be awarded a point. Furthermore, no point would be awarded if the answer only mentioned connection/correlation, without specifying that it was between something, such as small particles. Afterwards, the first coder coded the remaining 1,009 answers.

A4.3 Control variables

Awareness of quantum. Prior awareness of quantum technology can influence comprehension when participants use it as a cue for assessment (Thiede et al., 2010) and can furthermore influence participants' attitudes with more aware participants holding more favourable attitudes (see Scheufele & Lewenstein, 2005 in the case of nanotechnology). To control for this effect, participants were asked (Scheufele & Lewenstein, 2005): *"How much have you heard, read or seen about the following technologies?" "Solar energy, Biotechnology, Quantum technology, Artificial Intelligence, Vaccines"* [1 = nothing at all, 7 = very much]. To mask the fact that we were only interested in awareness of quantum technology, we used 4 extra items shown in a random order, based on new technologies that were asked in the Special Eurobarometer 516 (European Commission, Directorate-General for Communication, 2021). In line with our expectations, awareness of quantum technology in the sample was low ($M = 2.78$, $SD = 1.60$), with 66.1% of participants (n = 773) indicating they had not heard about quantum technology at all or little [scores: 1-3]. Compared to the other new technologies that we asked about, participants scored on average lowest for awareness of quantum technology (see Figure A8).

Figure A8

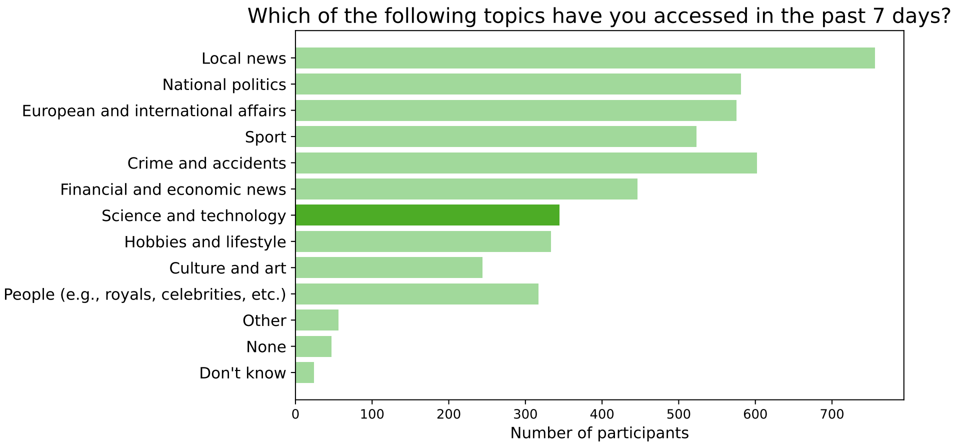
Awareness of quantum technology in comparison to other new technologies. The plots are centred around the neutral (Likert score of 4) value. (Figure created through adaptation of this Github file).



Science news use. People who tend to read the science news section in newspapers (the most popular section in which articles on quantum science and technology appear; Chapter 3) might hold more positive views on quantum technology compared to people who skip this section (see e.g., Scherrer, 2023; Scheufele & Lewenstein, 2005). Therefore, we measured participants' science news use with the item (European Parliament, 2023): *"Thinking about news and other information, which of the following topics have you accessed in the past 7 days? (Multiple answers allowed)": "Local news, National politics, European and international affairs, Sport, Crime and accidents, Financial and economic news, Science and technology, Hobbies and lifestyle, Culture and art, People (e.g., royals, celebrities, etc.), Other, None, Don't know"*. We found a total of n = 344 (29.5%) had accessed science news in the past 7 days, which is slightly higher than the 24% found in 2023 by the Eurobarometer (European Parliament, 2023).

Figure A9

News use of the participants in our sample, where science news use indicates the answer 'Science and technology'.



Interest in new technology. People may use interest in a topic as a cue to judge their comprehension of a text (Thiede et al., 2010). We measured participants' interest in new technologies with 6 items adapted from Shulman et al. (2020) ("science technologies" was substituted for "new technologies"): *"I am interested in learning about new technologies", "I find the debate surrounding new technologies interesting", "I want to learn more about new technologies", "New technologies are exciting", "I find new technology boring"* (reverse coded), *"New technological ideas are thought-provoking"* [1 = strongly disagree, 7 = strongly agree]. These six items were averaged into an index ($M = 4.40$, $SD = 1.29$, Cronbach's $\alpha = 0.91$).

Faith in intuition. People who have a high faith in intuition tend to rely more on affect (van Giesen et al., 2018). Therefore, we measured participants' faith in intuition with 5 items (Epstein et al., 1996): *"I trust my initial feelings about people", "I believe in trusting my hunches", "My initial impressions of people are almost always right", "When it comes to trusting people, I can usually rely on my "gut feelings." ", "I can usually feel when a person is right or wrong even if I can't explain how I know."* [1 = completely false, 7 = completely true]. The five items were averaged into an index ($M = 4.87$, $SD = 0.95$, Cronbach's $\alpha = 0.86$).

Need for cognition. People who have a high need for cognition rely more on cognition (van Giesen et al., 2018). The 5 items were (Epstein et al., 1996): *"I don't like to have to do a lot of thinking"* (reverse coded), *"I try to avoid situations that require thinking in depth about something"* (reverse coded), *"I prefer to do something that challenges my thinking abilities rather than something that requires* *little thought", "I prefer complex to simple problems", "Thinking hard and for a long time about something gives me little satisfaction* (reverse coded)" [1 = completely false, 7 = completely true]. The five items were averaged into an index ($M = 4.57$, $SD = 1.05$, Cronbach's $\alpha = 0.75$).

A4.4 Expert insights study

Table A17 shows the metaphors presented to the experts in the expert insights study in preparation of the experiment. Note that we have slightly modified the wording of the coin and dice metaphor in the experiment in a few places compared to the text presented to the experts, in order to make the texts as similar as possible in structure to the non-metaphorical version of the text. However, the metaphorical content has not changed.

Table A17

The metaphors used in the expert insights study, which were generated by ChatGPT 3.5 and modified to ensure similar structure.

Metaphor	Original Dutch text	Translated English text
Superposition		
A coin spinning in the air	Quantumsuperpositie is als een munt die in de lucht draait. Totdat we de munt op tafel slaan, is het alsof de munt tegelijkertijd kop en munt is. Echter, zodra we de munt op tafel slaan, komt de munt op kop óf munt terecht. Dit illustreert hoe deeltjes in de quantumwereld tegelijkertijd in meerdere toestanden kunnen bestaan totdat ze worden gemeten of waargenomen, net zoals een munt zowel kop als munt is totdat we de munt op tafel slaan.	Quantum superposition is like a coin spinning in the air. Until we hit the coin on the table, it is as if the coin is both heads and tails at the same time. However, as soon as we hit the coin on the table, the coin lands either heads or tails. This illustrates how particles in the quantum world can exist in multiple states at the same time until they are measured or observed, just as a coin is both heads and tails until we hit it on the table.

Metaphor	Original Dutch text	Translated English text
A radio producing a jumble of sounds	Quantumsuperpositie is als een radio die een wirwar aan geluiden voortbrengt. Totdat de radio-ontvanger aan een zender is gekoppeld, is het alsof de radio tegelijkertijd op alle mogelijke zenders is afgestemd. Echter, zodra de radio-ontvanger aan een zender is gekoppeld, stemt de radio meteen nog maar op één van de mogelijke zenders af. Dit illustreert hoe deeltjes in de quantumwereld tegelijkertijd in meerdere toestanden kunnen bestaan totdat ze worden gemeten of waargenomen, net zoals de radio op alle mogelijke zenders is afgestemd totdat de radio-ontvanger aan een zender is gekoppeld.	Quantum superposition is like a radio that produces a jumble of sounds. Until the radio receiver is hooked up to a transmitter, it is as if the radio is tuned to all possible channels at once. However, as soon as the radio receiver is hooked up to a transmitter, the radio immediately tunes to only one of the possible channels. This illustrates how particles in the quantum world can exist in multiple states at once until they are measured or observed, just as the radio is tuned to all possible channels until the radio receiver is hooked up to a transmitter.
A cat, a vial of poison and a radioactive atom in a locked box	Quantumsuperpositie is als een kat, een flesje gif en een radioactief atoom in een afgesloten doos. Totdat we de doos openen, is het alsof de kat tegelijkertijd levend en dood is. Echter, zodra we de doos openen zien we dat óf het atoom is vervallen waardoor het flesje gif is gebroken en de kat is gedood, óf dat het atoom niet is vervallen en de kat levend is. Dit illustreert hoe deeltjes in de quantumwereld tegelijkertijd in meerdere toestanden kunnen bestaan totdat ze worden gemeten of waargenomen, net zoals een kat zowel levend als dood is totdat we de doos openen.	Quantum superposition is like a cat, a vial of poison, and a radioactive atom in a sealed box. Until we open the box, it is as if the cat is both alive and dead at the same time. However, once we open the box, we see that either the atom has decayed, breaking the vial of poison and killing the cat, or the atom has not decayed and the cat is alive. This illustrates how particles in the quantum world can exist in multiple states at the same time until they are measured or observed, just as a cat is both alive and dead until we open the box.

Metaphor	Original Dutch text	Translated English text
An artist dabbing his brush in multiple colours	Quantumsuperpositie is als een kunstenaar die zijn penseel in meerdere kleuren dept. Totdat het penseel het canvas raakt, is het alsof het penseel tegelijkertijd in alle mogelijke kleurencombinaties aanwezig is. Echter, zodra het penseel het canvas raakt, laat het canvas meteen nog maar één van de mogelijke kleurencombinaties zien. Dit illustreert hoe deeltjes in de quantumwereld tegelijkertijd in meerdere toestanden kunnen bestaan totdat ze worden gemeten of waargenomen, net zoals het penseel zich in alle mogelijke kleurencombinaties bevindt totdat het penseel het canvas raakt.	Quantum superposition is like an artist dabbing his brush in multiple colors. Until the brush touches the canvas, it is as if the brush is in all possible color combinations at the same time. However, as soon as the brush touches the canvas, the canvas immediately shows only one of the possible color combinations. This illustrates how particles in the quantum world can exist in multiple states at the same time until they are measured or observed, just as the brush is in all possible color combinations until it touches the canvas.
A musician composing a music piece	Quantumsuperpositie is als een muzikant die een muziekstuk componeert en meerdere muzieknoten op hetzelfde blad plaatst. Totdat de muzikant de partituur speelt, is het alsof de muziek zich tegelijkertijd in alle mogelijke melodieën bevindt. Echter, zodra de muzikant de partituur speelt, bevindt de muziek zich meteen nog maar in één van de mogelijke melodieën. Dit illustreert hoe deeltjes in de quantumwereld tegelijkertijd in meerdere toestanden kunnen bestaan totdat ze worden gemeten of waargenomen, net zoals de muziek zich in alle mogelijke melodieën bevindt totdat de muzikant de partituur speelt.	Quantum superposition is like a musician composing a piece of music and placing multiple notes on the same sheet of paper. Until the musician plays the score, it is as if the music is in all possible melodies at once. However, as soon as the musician plays the score, the music is immediately in only one of the possible melodies. This illustrates how particles in the quantum world can exist in multiple states at once until they are measured or observed, just as the music is in all possible melodies until the musician plays the score.
Entanglement		

Metaphor	Original Dutch text	Translated English text
A pair of dice	Quantumverstrengeling is als het gooien van een paar dobbelstenen. Wanneer de ene dobbelsteen wordt gegooid, is de uitkomst van de andere dobbelsteen vooraf bepaald, zelfs als deze aan de andere kant van de speeltafel wordt gegooid. Dit illustreert hoe in de quantumwereld de toestand van het ene deeltje de toestand bepaalt van het deeltje waarmee het verstrengeld is, net zoals de uitkomst van de ene dobbelsteen de uitkomst van de andere dobbelsteen bepaalt.	Quantum entanglement is like rolling a pair of dice. When one die is rolled, the outcome of the other die is predetermined, even if it is rolled on the other side of the gaming table. This illustrates how in the quantum world, the state of one particle determines the state of the particle it is entangled with, just as the outcome of one die determines the outcome of the other die.
Two dancers performing a perfectly synchronized dance routine	Quantumverstrengeling is als twee dansers die een perfect gesynchroniseerde dansroutine uitvoeren. Wanneer de ene danser beweegt, beweegt de andere danser op een gecoördineerde manier alsof ze een onzichtbare link delen, zelfs als ze zich aan andere kanten van het podium bevinden. Dit illustreert hoe in de quantumwereld de toestand van het ene deeltje de toestand bepaalt van het deeltje waarmee het verstrengeld is, net zoals de bewegingen van de ene danser de bewegingen van de andere danser bepalen.	Quantum entanglement is like two dancers performing a perfectly synchronized dance routine. When one dancer moves, the other dancer moves in a coordinated manner as if they share an invisible link, even if they are on opposite sides of the stage. This illustrates how in the quantum world, the state of one particle determines the state of the particle it is entangled with, just as the movements of one dancer determine the movements of the other dancer.
A telepathic twin	Quantumverstrengeling is als een telepathische tweeling die onmiddellijk elkaars gedachten kan kennen. Wanneer de ene tweeling van gedachten verandert, verandert de ander onmiddellijk ook van gedachten, zelfs als ze zich aan andere kanten van de planeet bevinden. Dit illustreert hoe in de quantumwereld de toestand van het ene deeltje de toestand bepaalt van het deeltje waarmee het verstrengeld is, net zoals de gedachten van de ene tweeling de gedachten van de andere tweeling bepalen.	Quantum entanglement is like a pair of telepathic twins who can instantly know each other's thoughts. When one twin changes their mind, the other instantly changes their mind too, even if they are on opposite sides of the planet. This illustrates how in the quantum world, the state of one particle determines the state of the particle it is entangled with, just as the thoughts of one twin determine the thoughts of the other twin.

Metaphor	Original Dutch text	Translated English text
Two compass needles that always point in opposite directions	Quantumverstrengeling is als het hebben van twee kompasnaalden die altijd in tegengestelde richtingen wijzen. Wanneer je de ene naald naar het noorden draait, wijst de andere onmiddellijk naar het zuiden, ook al bevinden ze zich aan de andere kant van de zeilboot. Dit illustreert hoe in de quantumwereld de toestand van het ene deeltje de toestand bepaalt van het deeltje waarmee het verstrengeld is, net zoals het draaien van de naald van het ene kompas de naald van het andere kompas aanpast.	Quantum entanglement is like having two compass needles that always point in opposite directions. When you turn one needle north, the other immediately points south, even though they are on opposite sides of the sailboat. This illustrates how in the quantum world, the state of one particle determines the state of the particle it is entangled with, just as turning the needle of one compass adjusts the needle of the other compass.
Two clocks with perfectly synchronized second hands	Quantumverstrengeling is als twee klokken waarvan de secondewijzers perfect gesynchroniseerd zijn. Wanneer u de tijd op de ene klok wijzigt, past de andere zich onmiddellijk aan, zelfs als deze zich aan de andere kant van de kamer bevindt. Dit illustreert hoe in de quantumwereld de toestand van het ene deeltje de toestand bepaalt van het deeltje waarmee het verstrengeld is, net zoals het veranderen van de tijd op de ene klok de tijd op de andere klok aanpast.	Quantum entanglement is like two clocks with perfectly synchronized second hands. When you change the time on one clock, the other clock immediately adjusts, even if it is across the room. This illustrates how in the quantum world, the state of one particle determines the state of the particle it is entangled with, just as changing the time on one clock changes the time on the other clock.

A4.5 The variety of explanations from experts for their rankings

Table A18 shows the variety of answers given to the question: “If you were to use a comparison in a conversation with non-quantum experts about quantum superposition/quantum entanglement, which of these would you use? Rank them in order from most likely to least likely.”

Table A18

Answers to the question 'Please explain your ranking'. Answers are grouped, translated and edited for clarity.

Superposition		
Metaphor	Positive	Negative
A coin spinning in the air	1. The metaphor best illustrates that the outcome of the measurement is indeterminate until a measurement is performed. 2. The metaphor provides the most minimalistic and simplest explanation. 3. The metaphor lends itself best to subsequently explain other concepts such as entanglement, measurement, quantum key distribution etc. 4. The metaphor best illustrates that a measurement provides a kind of probability of different outcomes. 5. The metaphor appeals to the imagination of people and appeals to the largest audience.	1. The metaphor explains what chance is (classical statistics), not what superposition is. 2. The metaphor does not take into account that you can change bases.
A radio producing a jumble of sounds	1. The metaphor best illustrates that superpositions are real, in the sense that they were not simply randomly generated. 2. The metaphor is most accurate, because it explicitly places the importance of a measurement in the description.	1. The metaphor brings with it all sorts of nuances that only confuse people more. 2. The metaphor is not correct. 3. The metaphor is incomprehensible. 4. The metaphor is too specific, which means it only appeals to the imagination of a limited number of people.
A cat, a vial of poison and a radioactive atom in a locked box	1. The metaphor is very well known and therefore resonates better. 2. The metaphor is nice to explain entanglement.	1. The metaphor is not correct. 2. The metaphor is too complicated to convey. 3. The metaphor is too specific, which means it only appeals to the imagination of a limited number of people.

Metaphor	Positive	Negative
An artist dabbing his brush in multiple colours		1. The metaphor brings all kinds of nuances that only confuse people more. 2. The metaphor unnecessarily brings the problem of mixing colour into it. 3. The metaphor is not valid. 4. The metaphor does not illustrate the quantum aspect enough, because if you dab a brush in multiple colours, there will probably be multiple colours on the canvas. 5. The metaphor is too specific, which means that it only appeals to the imagination of a limited number of people.
A musician composing a music piece	1. The metaphor is valid.	1. The metaphor brings with it all kinds of nuances that only confuse people more. 2. The metaphor is incomprehensible / complicated because of the many outcomes. 3. The metaphor does not illustrate the quantum aspect enough, because the musician can choose what he is going to play (in a quantum measurement we cannot choose what the outcome of the measurement will be). 4. The metaphor is worded too unclearly. 5. The metaphor is too specific, which means that it only appeals to the imagination of a limited number of people.
Entanglement		

Metaphor	Positive	Negative
A pair of dice	1. The metaphor illustrates that the outcome is not known in advance. 2. The metaphor illustrates that a 'measurement' is performed on one part of the entangled state which determines the state of the other part. 3. The metaphor illustrates the probabilistic collapse of the wave function of an entangled state. 4. The metaphor illustrates the 'random' character. 5. The metaphor illustrates that probability is a description of our knowledge. 6. The metaphor is very simple and precise.	1. The metaphor says that the state of the other die is known "automatically", while the states of the two dice are correlated in a way that is not classically possible. 2. The metaphor does not illustrate the superposition part, namely that both particles are in different states at the same time, until it is determined. 3. The metaphor misses the instantaneous.
Two dancers performing a perfectly synchronized dance routine		1. The metaphor implies communication by comparing it to humans, while one of the most common misconceptions about entanglement is that you can communicate faster than the speed of light. 2. The dancers can rehearse the dance in advance, so it is not strange that the dancers dance exactly in (anti)phase, that is routine. People can consciously perform actions and synchronize that. 3. The metaphor is too vague. 4. The metaphor suggests 'spooky action at a distance', which is the most misunderstood aspect of entanglement.

Metaphor	Positive	Negative
A telepathic twin	1. The metaphor uses a much larger distance (other side of the planet). 2. The metaphor has somewhere the idea that there is not necessarily a predetermined local variable (at least, if we assume free will etc.). 3. The metaphor emphasizes the immediate nature of entanglement (the state of the second is determined immediately).	1. The ‘determination’ in the mind is disturbing. 2. The metaphor implies communication by comparing it to people, while one of the most common misconceptions about entanglement is that you can communicate faster than the speed of light. 3. Suggesting telepathy is not ideal. 4. The metaphor suggests ‘spooky action at a distance’, which is the most misunderstood aspect of entanglement. 5. Two people can consciously perform actions and then synchronize them. 6. The element of chance is missing where a measurement in one place projects the entire quantum entangled system from an ‘indeterminate state’ to a combined fixed final state.
Two compass needles that always point in opposite directions	1. The metaphor is intuitively clearest because the action does not come from within, but is commanded externally.	1. The state is always visible and so there is a kind of analogue state. 2. The compasses could still be linked via a magnetic field. 3. The metaphor describes a kind of non-existent correlation that is not quantum mechanical, but also not classical. 4. The metaphor suggests ‘spooky action at a distance’, which is the most misunderstood aspect of entanglement. 5. Entanglement cannot be used to cause changes at a distance, like a compass needle that you turn north.

Metaphor	Positive	Negative
Two clocks with perfectly synchronized second hands	1. The metaphor is nice. 2. The metaphor is intuitively the clearest, because the action does not come from within, but is externally ordered.	1. This gives all sorts of issues with the theory of relativity. 2. The time in both clocks is a very clear local variable, and therefore resembles most 'normal' classical correlation. The state is always visible and therefore there is a kind of analogue state. 3. The metaphor describes a kind of non-existent correlation that is not quantum mechanical, but also not classical. 4. The superposition is missing. 5. If two particles are entangled, one of the particles can still be adjusted independently of the other by means of, in jargon, a "local transformation". What changes is the correlation. Hence, an active change on one particle influences the other particle does not apply. 6. The metaphor suggests 'spooky action at a distance', which is the most misunderstood aspect of entanglement. 7. Entanglement cannot be used to cause changes at a distance, like changing the time of a clock.

A4.6 Tables for the mediation analyses

Table A19

The indirect, component (path a and b), direct (path c') and total effects from the mediation analyses with perceived comprehension (PC) as a mediator. The contrasts used are: 1 vs. 2 = control – non-metaphorical and 1 vs. 3 = control – metaphorical. 'Cogn.' refers to cognition.

Non-metaphorical – Control, PC as mediator								
Type	Effect	Estimate	SE	Lower	Upper	β	z	p
Indirect	1 vs. 2 ⇒ PC ⇒ Affect	-0.13	0.04	-0.21	-0.06	-0.07	-3.64	$<$ .001
	1 vs. 2 ⇒ PC ⇒ Cogn.	-0.12	0.03	-0.19	-0.05	-0.06	-3.52	$<$ .001
Path a	1 vs. 2 ⇒ PC	-0.32	0.09	-0.48	-0.15	-0.12	-3.73	$<$ .001
Path b	PC ⇒ Affect	0.42	0.02	0.39	0.46	0.55	21.33	$<$ .001
	PC ⇒ Cogn.	0.38	0.02	0.33	0.42	0.46	16.48	$<$ .001
Path c'	1 vs. 2 ⇒ Affect	0.09	0.05	-0.01	0.21	0.05	1.76	0.079
	1 vs. 2 ⇒ Cogn.	0.04	0.06	-0.09	0.17	0.02	0.65	0.519
Total	1 vs. 2 ⇒ Affect	-0.04	0.07	-0.17	0.09	-0.02	-0.58	0.565
	1 vs. 2 ⇒ Cogn.	-0.08	0.07	-0.22	0.06	-0.04	-1.11	0.266
Metaphorical – Control, PC as mediator								
Type	Effect	Estimate	SE	Lower	Upper	β	z	p
Indirect	1 vs. 3 ⇒ PC ⇒ Affect	-0.12	0.04	-0.20	-0.05	-0.06	-3.37	$<$ .001
	1 vs. 3 ⇒ PC ⇒ Cogn.	-0.11	0.03	-0.18	-0.05	-0.05	-3.28	0.001
Path a	1 vs. 3 ⇒ PC	-0.29	0.08	-0.46	-0.13	-0.11	-3.41	$<$ .001
Path b	PC ⇒ Affect	0.42	0.02	0.39	0.46	0.55	21.33	$<$ .001
	PC ⇒ Cogn.	0.38	0.02	0.33	0.42	0.46	16.48	$<$ .001
Path c'	1 vs. 3 ⇒ Affect	0.01	0.05	-0.10	0.12	0.01	0.22	0.826
	1 vs. 3 ⇒ Cogn.	-0.02	0.06	-0.14	0.10	-0.01	-0.38	0.708
Total	1 vs. 3 ⇒ Affect	-0.11	0.07	-0.24	0.01	-0.06	-1.70	0.089
	1 vs. 3 ⇒ Cogn.	-0.13	0.07	-0.26	0.00	-0.06	-1.96	0.050

Note. Indirect = Path a * Path b, Total = Indirect + Path c', z-statistic = Estimate / SE. Betas are completely standardized effect sizes.

Table A20

The indirect, component (path a and b), direct (path c') and total effects from the mediation analyses with actual comprehension (AC) as a mediator. The contrasts used are: 1 vs. 2 = control – non-metaphorical and 1 vs. 3 = control – metaphorical. ‘Cogn.’ refers to cognition.

Non-metaphorical – Control, AC as mediator								
Type	Effect	Estimate	SE	Lower	Upper	β	z	p
Indirect	1 vs. 2 ⇒ AC ⇒ Affect	0.15	0.02	0.11	0.19	0.07	6.91	$<$ .001
	1 vs. 2 ⇒ AC ⇒ Cogn.	0.15	0.02	0.11	0.20	0.07	6.39	$<$ .001
Path a	1 vs. 2 ⇒ AC	0.43	0.05	0.33	0.54	0.26	8.22	$<$ .001
Path b	AC ⇒ Affect	0.34	0.03	0.27	0.40	0.28	10.26	$<$ .001
	AC ⇒ Cogn.	0.35	0.04	0.27	0.42	0.27	9.40	$<$ .001
Path c'	1 vs. 2 ⇒ Affect	-0.18	0.07	-0.31	-0.05	-0.09	-2.71	0.007
	1 vs. 2 ⇒ Cogn.	-0.23	0.07	-0.37	-0.09	-0.11	-3.32	$<$ .001
Total	1 vs. 2 ⇒ Affect	-0.04	0.07	-0.17	0.09	-0.02	-0.57	0.566
	1 vs. 2 ⇒ Cogn.	-0.08	0.07	-0.22	0.06	-0.04	-1.11	0.266
Metaphorical – Control, AC as mediator								
Type	Effect	Estimate	SE	Lower	Upper	β	z	p
Indirect	1 vs. 3 ⇒ AC ⇒ Affect	0.10	0.02	0.07	0.14	0.05	5.77	$<$ .001
	1 vs. 3 ⇒ AC ⇒ Cogn.	0.11	0.02	0.07	0.15	0.05	5.65	$<$ .001
Path a	1 vs. 3 ⇒ AC	0.31	0.05	0.21	0.40	0.19	6.32	$<$ .001
Path b	AC ⇒ Affect	0.34	0.03	0.27	0.40	0.28	10.26	$<$ .001
	AC ⇒ Cogn.	0.35	0.04	0.27	0.42	0.27	9.40	$<$ .001
Path c'	1 vs. 3 ⇒ Affect	-0.22	0.07	-0.35	-0.09	-0.11	-3.31	$<$ .001
	1 vs. 3 ⇒ Cogn.	-0.24	0.07	-0.37	-0.11	-0.11	-3.55	$<$ .001
Total	1 vs. 3 ⇒ Affect	-0.11	0.07	-0.24	0.02	-0.06	-1.66	0.097
	1 vs. 3 ⇒ Cogn.	-0.13	0.07	-0.27	0.00	-0.06	-1.94	0.053

Note. Indirect = Path a * Path b, Total = Indirect + Path c', z-statistic = Estimate / SE. Betas are completely standardized effect sizes.

Samenvatting

Quantumtechnologie is een opkomende technologie van de 21e eeuw die naar verwachting aanzienlijke positieve en negatieve gevolgen zal hebben voor de samenleving. Voorbeelden van mogelijke positieve gevolgen zijn het ontwerpen van nieuwe geneesmiddelen, de mogelijkheid van veilig online stemmen en de veiligere bouw van energie- en transportinfrastructuur. Voorbeelden van mogelijke negatieve gevolgen zijn echter het kraken van onze encryptie, wat kan leiden tot datalekken, het verliezen van grip op criminele organisaties die via quantumcommunicatie op een fundamenteel veilige manier met elkaar kunnen communiceren, en ethische en privacykwesties als gevolg van grote hoeveelheden sensorgegevens. Om de positieve maatschappelijke impact van quantumtechnologie te maximaliseren en de negatieve impact te minimaliseren, kan publieke betrokkenheid belangrijk zijn. Door maatschappelijke actoren te laten deelnemen aan dialogen over quantumtechnologie, kan er beter inzicht ontstaan in hoe quantumtechnologie verschillende groepen mensen beïnvloedt. Ook kan publieke betrokkenheid leiden tot meer publieke steun voor, en minder publieke weerstand tegen, quantumtechnologie. Bovendien zouden mensen vanuit democratisch perspectief de kans moeten krijgen om deel te nemen aan dialogen over quantumtechnologie, aangezien deze technologie een aanzienlijke invloed kan gaan hebben op hun leven. **Hoofdstuk 1** beschrijft het veld van quantumwetenschap en -technologie en de rol die wetenschapscommunicatie kan spelen in een dergelijke ontwikkeling in meer detail.

Dit proefschrift onderzoekt de publieke communicatie rond quantumwetenschap en -technologie die van invloed kan zijn op de betrokkenheid van het publiek. Wetenschappelijke literatuur wijst op vier mogelijke problemen in de publieke communicatie over quantumwetenschap en -technologie die de betrokkenheid van het publiek kunnen belemmeren. Deze zijn:

(a) het framen van quantumwetenschap en -technologie als iets raadselachtigs;

(b) de onderliggende quantumfenomenen niet behandelen bij het uitleggen van wat quantumtechnologie inhoudt;

(c) het gebruik van een 'beperkt' in plaats van een 'breder' publiekbelangframe; en

(d) de focus op het domein van quantumcomputing & -simulatie ten koste van de andere twee domeinen van quantumtechnologie (namelijk quantumcommunicatie en quantumsensing & -metrologie).

Hoofdstuk 2 en **Hoofdstuk 3** beschrijven of deze vier mogelijke problemen daadwerkelijk voorkomen in de publieke communicatie over quantumwetenschap en -technologie. Hiervoor hebben we een inhoudsanalyse uitgevoerd van 501 Engelstalige TEDx presentaties (Hoofdstuk 2) en 385 Nederlandse krantenartikelen (Hoofdstuk 3) waarin informatie over quantumwetenschap en -technologie werd gedeeld.

We vonden zeer vergelijkbare resultaten voor beide datasets. Ten eerste kwam *het spookachtig en raadselachtigframe* in bijna een kwart van beide datasets voor, wat aantoont dat het frame weliswaar aanwezig was, maar niet in de meeste presentaties of artikelen voorkwam. Ten tweede bevatte ongeveer de helft van het geanalyseerde materiaal waarin naar quantumtechnologie werd verwezen ten minste één *uitleg voor een quantumfenomeen* dat wij meenamen in onze studie (superpositie, verstrengeling en contextualiteit). Ten derde werd in beide datasets nauwelijks verwezen naar hoe quantumtechnologie problemen kan oplossen of het leven van mensen kan verbeteren (beschouwd als een *breder publiekbelangframe*), of naar hoe quantumtechnologie economische ontwikkeling kan realiseren of tot concurrentie kan leiden (beschouwd als een *beperkt publiekbelangframe*). In een aanvullende analyse naar het voordeel- en het risicoframe leek het breder publiekbelangframe – dat een reflectie op zowel de voordelen als de risico's inhoudt – echter te ontbreken, aangezien de potentiële voordelen van quantumtechnologie in beide datasets ongeveer zes keer vaker werden genoemd dan de potentiële risico's. Ten slotte bleek in beide datasets de nadruk te liggen op *het domein van quantumcomputers en -simulatie*.

Na het kwantificeren van de mogelijke problemen in Hoofdstuk 2 en 3, beschrijft het onderzoek in **Hoofdstuk 4** hun effect op de betrokkenheid van mensen bij quantumtechnologie aan de hand van een online experiment. In totaal namen n = 637 volwassenen, representatief voor de Nederlandse bevolking, deel aan het experiment. De deelnemers werden willekeurig ingedeeld om een tekst te lezen waarin het bijvoeglijk naamwoord 'raadselachtig' al dan niet werd gebruikt bij de beschrijving van quantummechanica; waarin al dan niet een uitleg van een quantumfenomeen werd gegeven; en waarin al dan niet een voordeel-, risico-, zowel een voordeel- als risico-, of geen van deze frames werd gebruikt. Daarna werd de zelfgerapporteerde betrokkenheid van de deelnemers bij quantumtechnologie gemeten aan de hand van een schaal met verschillende variabelen: 1) de intentie van de deelnemers om aanvullende informatie over quantumtechnologie te zoeken (informatie zoeken); 2) hun overtuiging over hun eigen vermogen om informatie over quantumtechnologie te begrijpen en ermee om te gaan (internal efficacy); 3) hun algemene interesse in quantumtechnologie (algemene interesse); en 4) hun vertrouwen in hun kennis van quantumtechnologie (waargenomen kennis).

De resultaten toonden aan dat het raadselachtigframe en het risicoframe de zelfgerapporteerde betrokkenheid niet verhoogden of schaadden. Deelnemers die een uitleg over een quantumfenomeen hadden gelezen scoorden echter significant hoger op algemene interesse dan degenen die die uitleg niet hadden gelezen, en deelnemers die waren blootgesteld aan een voordeelframe scoorden significant hoger op internal efficacy dan degenen die dat niet waren. Deelnemers die echter een voordeel- én een risicoframe hadden gelezen scoorden significant lager op waargenomen kennis in vergelijking met degenen die alleen over een voordeel of alleen over een risico van quantumtechnologie hadden gelezen. Dit resultaat bracht een interessante spanning aan het licht, aangezien een aantal wetenschapscommunicatieonderzoekers hebben betoogd dat voor de grootste positieve maatschappelijke impact een brede reflectie op zowel de voordelen als de risico's van quantumtechnologie nodig is. In Hoofdstuk 4 stellen we dat deze ethische overweging naar onze mening belangrijker is om mee te nemen in de publieke communicatie over quantumtechnologie dan de mogelijke nadelen ervan.

In **Hoofdstuk 5** presenteren we vervolgens of metaforen belangrijke quantumfenomenen (superpositie en verstrengeling) begrijpelijker maken en of dit op zijn beurt van invloed is op de attitude van mensen ten aanzien van quantumtechnologie. Hiervoor maakten we gebruik van een online experiment waar in totaal n = 1.167 volwassenen, representatief voor de Nederlandse bevolking, aan deelnamen. Ze lazen een fictief nieuwsartikel dat ofwel een metaforische uitleg, ofwel een niet-metaforische uitleg of helemaal geen uitleg bevatte over superpositie of verstrengeling. Daarna werden vier variabelen gemeten: 1) het gevoel van de deelnemers van hun begrip van het nieuwsartikel (waargenomen begrip); 2) hun daadwerkelijke begrip van het genoemde quantumfenomeen (daadwerkelijk begrip); 3) hun emoties en gevoelens ten opzichte van quantumtechnologie (op affect gebaseerde attitude); en 4) hun gedachten en overtuigingen over quantumtechnologie (op cognitie gebaseerde attitude).

De metaforische uitleg van superpositie en verstrengeling in het nieuwsartikel was afkomstig van een kleinschalig onderzoek dat we hadden uitgevoerd onder n = 22 Nederlandse quantumexperts voorafgaand aan het experiment. In reactie op oproepen van de wetenschapscommunicatiegemeenschap om de nauwkeurigheid van door AI gegenereerde wetenschappelijke uitleg te evalueren, hebben we ChatGPT 3.5 vijf metaforen voor superpositie en vijf metaforen voor verstrengeling laten genereren, die de Nederlandse quantumexperts vervolgens evalueerden op accuraatheid. De meest accurate metafoor voor superpositie vergeleek het fenomeen met een munt die in de lucht ronddraait en tegelijkertijd kop en munt lijkt te zijn totdat de munt op tafel valt. De meest accurate metafoor voor verstrengeling vergeleek dit quantumfenomeen met het gooien van een paar dobbelstenen, waarbij als één dobbelsteen wordt gegooid, de uitkomst van de andere dobbelsteen vooraf bepaald is, zelfs als deze zich aan de andere kant van de goktafel bevindt.

De resultaten van ons experiment toonden aan dat deelnemers die een uitleg over een quantumfenomeen hadden gelezen, ongeacht of die uitleg metaforisch of niet-metaforisch was, hun waargenomen begrip van het nieuwsartikel aanzienlijk lager scoorden dan degenen die geen uitleg over een quantumfenomeen hadden gelezen. Het daadwerkelijke begrip van het quantumfenomeen van de uitleg-conditie groepen was echter aanzienlijk hoger dan van de geen-uitleg-conditie groepen. We vonden geen significante verschillen tussen de groepen wat betreft hun attitude ten opzichte van quantumtechnologie.

Aangezien eerder onderzoek een verband suggereert tussen begrip en attitude, hebben we dit verband ook in de context van ons onderzoek onderzocht. De effecten die we waarnamen waren significant maar zeer klein, en verschilden niet tussen metaforische en niet-metaforische uitleg. We ontdekten dat het geven van een uitleg over een quantumfenomeen in het nieuwsartikel het gevoel van begrip van de deelnemers aanzienlijk verminderde, wat op zijn beurt leidde tot minder positieve attitudes ten opzichte van quantumtechnologie. We ontdekten echter ook dat het geven van een uitleg over een quantumfenomeen het daadwerkelijke begrip van de deelnemers van het quantumfenomeen verhoogt, wat op zijn beurt juist tot positievere attitudes leidde ten opzichte van quantumtechnologie, maar dat dit positieve effect werd tenietgedaan door een direct negatief effect.

Ten slotte geeft **Hoofdstuk 6** een reflectie op de studies in dit proefschrift. We presenteren de beperkingen van het werk en het mogelijke vervolgonderzoek dat daaruit voortkomt, en sluiten af met vier aanbevelingen voor wetenschapscommunicatieonderzoekers en vier aanbevelingen voor wetenschapscommunicatoren.

Aanbevelingen voor wetenschapscommunicatieonderzoekers. De eerste aanbeveling voor onderzoekers op het gebied van wetenschapscommunicatie is dat, zoals in dit proefschrift wordt aangetoond, beweringen over mogelijke problemen empirisch moeten worden onderzocht om echt inzicht te krijgen in het voorkomen en de effecten ervan. Ten tweede lieten de inhoudsanalyses in dit proefschrift zeer vergelijkbare resultaten zien tussen Engelse TEDx presentaties en Nederlandse krantenartikelen. Toekomstig onderzoek zou moeten nagaan of deze patronen een algemene trend zijn in de publieke communicatie over quantumtechnologie. Ten derde hebben de experimentele studies in dit proefschrift aangetoond dat het soort informatie dat wordt verstrekt al van invloed kan zijn op de mening van mensen over quantumtechnologie. Daarom moet verder worden onderzocht hoe bepaalde communicatiebeslissingen over grotendeels onbekende onderwerpen verschillende publieken beïnvloeden. Ten slotte heeft dit proefschrift aangetoond dat het meten van de effecten van frames op variabelen die niet direct betrekking hebben op publieke steun, zoals de intentie van mensen om aanvullende informatie op te zoeken over een bepaald onderwerp of hun algemene interesse erin, belangrijke inzichten kan opleveren. Daarom dient dit verder onderzocht te worden.

Aanbevelingen voor wetenschapscommunicatoren. Ten eerste is het aan wetenschapscommunicatoren zelf om te beslissen of ze quantumwetenschap als iets spookachtigs of raadselachtigs willen presenteren, aangezien dit proefschrift laat zien dat een eenmalige vermelding hiervan geen voor- of nadelen lijkt te hebben voor publieke betrokkenheid. Ten tweede bleek uit de studies in dit proefschrift dat de keuze om in publieke communicatie al dan niet uitleg op te nemen over tegenintuïtieve quantumfenomenen afhangt van het doel van de communicatie. Als het doel is om de interesse in quantumtechnologie en de betrokkenheid bij quantumtechnologie in het algemeen te vergroten, of als het doel is om het begrip van het quantumfenomeen bij mensen (ietwat) te vergroten, kan uitleg helpen. Als het doel echter is om het publiek het gevoel te geven dat ze de communicatie zelf hebben begrepen, kunnen wetenschapscommunicatoren uitleg beter achterwege laten. Ten derde leken metaforen geen extra voordeel te bieden ten opzichte van niet-metaforen bij het uitleggen van quantumfenomenen. Het is dus aan wetenschapscommunicatoren zelf om te beslissen of ze metaforen gebruiken. Ze moeten echter wel voorzichtig zijn met het gebruik van metaforen die te complex of mysterieus zijn om over te brengen, om weerstand van experts te voorkomen. Ten slotte zou het goed zijn als wetenschapscommunicatoren aandacht besteden aan een breder scala aan quantumtechnologieën dan alleen quantumcomputers en de nadruk leggen op de potentiële voordelen en risico's ervan, om een gebalanceerd perspectief te presenteren.

Summary

Quantum technology is an emergent technology of the 21st century that is expected to have significant positive and negative consequences for society. Examples of possible positive consequences include the design of new medicines, the possibility of secure online voting, and the safer construction of energy and transportation infrastructure. However, negative consequences may include the breaking of our encryption, which may enable data breaches, the loss of control over criminal organisations that communicate with each other in a fundamentally secure way via quantum communication, and ethical and privacy issues resulting from large amounts of sensing data. To maximize the positive and minimize the negative impacts of quantum technology, public engagement could be important. Involving societal actors in dialogues about quantum technology could lead to a better understanding of how quantum technology affects different groups of people. Public engagement can also lead to greater public support for, and less resistance to, quantum technology. Furthermore, from a democratic perspective, people should be given the opportunity to participate in dialogues about quantum technology, as this technology could have a significant impact on their lives. **Chapter 1** describes the field of quantum science and technology and the role that science communication can play in such a development in more detail.

This dissertation examines public communication around quantum science and technology that may influence public engagement. Scientific literature points to four potential issues in public communication about quantum science and technology that may hinder its public engagement. These are:

(a) framing quantum science and technology as something enigmatic;

(b) skipping the underlying quantum phenomena when explaining what quantum technology entails;

(c) using a narrow instead of a wider public good frame; and

(d) focusing on the domain of quantum computing at the expense of the other two quantum technology domains (i.e., quantum communication and quantum sensing & metrology).

Chapter 2 and **Chapter 3** describe whether these four potential issues actually occur in public communication about quantum science and technology. To this end,

we conducted a content analysis of 501 English TEDx talks (Chapter 2) and 385 Dutch newspaper articles (Chapter 3) in which information about quantum science and technology was shared.

We found very similar results for both datasets. First, *the spooky and enigmatic frame* appeared in almost a quarter of both datasets, demonstrating that while the frame was present, it did not appear in the majority of talks or articles. Secondly, around half of the analysed material referencing quantum technology contained at least one *explanation for a quantum phenomenon* that we included in our study (superposition, entanglement and contextuality). Thirdly, in both datasets, there were hardly any references to how quantum technology can solve problems or improve people's lives (considered *a wider public good frame*), or to how quantum technology can realise economic development or lead to competition (considered *a narrow public good frame*). However, in an additional analysis of the benefit and risk frames, the wider public good frame – which constitutes a reflection on both the benefits and risks – seemed to be lacking, as the potential benefits of quantum technology were mentioned about six times more often than the potential risks in both datasets. Finally, both datasets showed an emphasis on *the domain of quantum computers and simulation*.

After quantifying the potential issues in Chapters 2 and 3, the study in **Chapter 4** describes their effect on people's engagement with quantum technology using an online experiment. A total of $n = 637$ adults, representative of the Dutch population, participated in the experiment. The participants were randomly assigned to read a text in which the adjective 'enigmatic' was used or not used in the description of quantum mechanics; in which an explanation of a quantum phenomenon was given or not given; and in which one of the following frames was used: benefit, risk, both a benefit and risk, or none of these. The participants' self-reported engagement with quantum technology was then measured using a scale with different variables: 1) the participants' intention to seek additional information about quantum technology (information seeking); 2) their belief in their own ability to understand and engage with information about quantum technology (internal efficacy); 3) their general interest in quantum technology (general interest); and 4) their confidence in their knowledge of quantum technology (perceived knowledge).

Results showed that the enigmatic frame and the risk frame neither increased nor harmed self-reported engagement. However, participants who had read an explanation of a quantum phenomenon scored significantly higher on general interest than those who had not read the explanation, and participants who had been exposed to a benefit frame scored significantly higher on internal efficacy than those who had not. However, participants who had read both a benefit and a risk frame scored significantly lower on perceived knowledge compared to those who had read only about a benefit or only about a risk of quantum technology. This result revealed an interesting tension, as a number of science communication researchers have argued that broad reflection on both the benefits and risks of quantum technology is necessary for the greatest positive societal impact. In Chapter 4, we argue that, in our view, this ethical consideration is more important to consider in public communication about quantum technology than its potential drawbacks.

In **Chapter 5**, we present whether metaphors make important quantum phenomena (superposition and entanglement) more comprehensible and whether this, in turn, influences people's attitudes towards quantum technology. We used an online experiment in which a total of n = 1,167 adults, representative of the Dutch population, participated. They read a fictional news article that contained either a metaphorical explanation, a non-metaphorical explanation, or no explanation at all about superposition or entanglement. Afterwards, four variables were measured: 1) the participants' beliefs about their understanding of the news article (perceived comprehension); 2) their actual understanding of the quantum phenomenon (actual comprehension); 3) their emotions and feelings towards quantum technology (affect-based attitude); and 4) their thoughts and beliefs about quantum technology (cognition-based attitude).

The metaphorical explanation of superposition and entanglement in the news article came from a small-scale study we conducted among n = 22 Dutch quantum experts prior to the experiment. In response to calls from the science communication community to evaluate the accuracy of AI-generated scientific explanations, we had ChatGPT 3.5 generate five metaphors for superposition and five metaphors for entanglement, which the Dutch quantum experts then evaluated for accuracy. The most accurate metaphor for superposition compared the phenomenon to a coin spinning in the air, which is heads and tails at the same time until the coin hits the table. The most accurate metaphor for entanglement compared it to rolling a pair of dice, where if one die is rolled, the outcome of the other die is predetermined, even if it is on the other side of the gambling table.

The results of our experiment showed that participants who had read an explanation of a quantum phenomenon, regardless of whether that explanation was metaphorical or non-metaphorical, scored their perceived comprehension of the news article significantly lower than those who had not read an explanation of a quantum phenomenon. However, the actual comprehension of the quantum phenomenon among the explanation-condition groups was significantly higher than among the no-explanation-condition groups. We found no significant differences between the groups in terms of their attitude towards quantum technology.

Since previous research suggests a relationship between comprehension and attitude, we also investigated this relationship in the context of our study. The effects we observed were significant but very small, and did not differ between metaphorical and non-metaphorical explanations. We found that providing an explanation of a quantum phenomenon in the news article significantly reduced participants' feelings of understanding the news article, which in turn led to less positive attitudes towards quantum technology. However, we also found that providing an explanation of a quantum phenomenon increased participants' actual understanding of the quantum phenomenon, which in turn led to more positive attitudes towards quantum technology, but that this positive effect was counteracted by a direct negative effect.

Finally, **Chapter 6** reflects on the studies in this dissertation. We present the limitations of the work and the possible follow-up research that arises from it, and conclude with four recommendations for science communication researchers and four recommendations for science communicators.

Recommendations for science communication researchers. The first recommendation for science communication researcher is that, as demonstrated in this dissertation, claims about potential issues should be empirically examined to gain true insight into their occurrence and effects. Second, the content-analytical studies in this dissertation showed very similar results between English TEDx talks and Dutch newspaper articles. Future research should investigate whether these patterns are a general trend in public communication about quantum technology. Third, the experimental studies in this dissertation showed that the type of information provided can already shape people's views of quantum technology. Therefore, investigations into how certain communication decisions about largely unfamiliar topics shape outcomes should be continued. And finally, this dissertation demonstrated that measuring the effects of frames on variables that are not directly about public support can provide important insights into engagement. This therefore warrants further investigation.

Recommendations for science communicators. First, it is up to science communicators themselves to decide whether or not to present quantum science as something spooky or enigmatic, as a brief, single mention seems to have no advantage or disadvantage to public engagement. Second, the studies in this dissertation showed that whether or not to include explanations of counterintuitive quantum phenomena in public communication depends on the goal of the communication. If the goal is to increase interest in quantum technology, and engagement with quantum technology in general, or if the goal is to (slightly) increase people's understanding of the quantum phenomenon, explanations may help. However, if the goal is to make your audience feel that they have understood the communication itself, explanations

are better omitted. Third, metaphors seemed to offer no additional advantage over non-metaphors in explaining quantum phenomena. It is therefore up to science communicators themselves to decide whether to use metaphors. However, they should be cautious about using metaphors that are too complex or mysterious to convey, to avoid resistance from experts. And finally, science communicators should pay attention to a broader range of quantum technologies than only quantum computers and emphasize their potential benefits and risks, to present a balanced perspective.

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Curriculum Vitae

Aletta Lucia Meinsma was born on January 20, 1996 in Nieuwegein. In 2014, she completed her pre-university education at Anna van Rijn College and Junior College Utrecht (JCU), after which she started her studies in Applied Physics. The first three years of her studies in Applied Physics were at Eindhoven University of Technology, where she obtained her Bachelor of Science degree in 2017. During the courses, she discovered that quantum science and technology appealed to her the most and decided to pursue a master's degree in Applied Physics with the track Quantum Nanoscience at Delft University of Technology. During her master's, she completed her thesis at QuTech (a collaboration between TU Delft and TNO) as an experimental researcher in the Quantum Internet and Networked Computing roadmap under the supervision of dr.ir. Tim Taminiau. Furthermore, she joined the Quantum Internet Vision Team as a student assistant and was responsible for the content of the Quantum Internet magazine that has as a goal to share TU Delft's vision on quantum internet research with a general audience.

After finishing her thesis, Aletta lived in Melbourne, Australia for half a year, where she worked as an intern at CSIRO (Australia's national scientific research agency, comparable to TNO in the Netherlands). At CSIRO, she developed new scripts for analyzing data from the CSIRO Energy Labs. After returning to the Netherlands, she worked as a communications advisor for QuTech and Quantum Delft, where she was responsible for translating research in quantum mechanics and technology into impactful content via press releases and news articles.

The last four years, Aletta worked as a PhD candidate under the supervision of dr.ir. Julia Cramer, dr. Gudrun Reijnierse and prof.dr.ir. Ionica Smeets on bridging the fields of science communication and quantum technology. During this period she obtained funding for a research visit with dr. Gudrun Reijnierse at the VU, and organized a research symposium on the role of language in engaging the public with new (quantum) technology. She also performed many different outreach events, wrote several blogs and was a quantum expert at the Quantuuuuhm podcast of the Universiteit van Nederland.

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Although not listed in the official author list, I was part of the TU Delft Vision Teams that published these magazines, and contributed to the content.

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