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Mapping the communication of science

(Mapeando la comunicación científica)

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ABSTRACT: Science communication is a broad field and involves very diverse activities. This paper aims to illuminate and partly systematise the diversity of science communication. We focus on three important dimensions: size of the audience, frequency of interaction, and decision-making relevance. Based on them, we introduce a three-dimensional space of science communication wherein particular scenarios can be located. We argue that relevant challenges for science communication are particularly associated with certain areas of this space. Based on the proposed framework, we also address potential strategies and developments in science communication.

Palabras clave

Comunicación científica
Encuadre
Fatiga de mensaje
Negacionismo de la ciencia

RESUMEN: La comunicación científica es un campo amplio que abarca actividades muy diversas. Este artículo tiene como propósito esclarecer y sistematizar parcialmente dicha diversidad. Nos centramos en tres dimensiones clave: el tamaño de la audiencia, la frecuencia de interacción y la relevancia para la toma de decisiones. A partir de estas dimensiones, proponemos un espacio tridimensional de la comunicación científica en el que pueden ubicarse los escenarios particulares. Sostenemos que ciertos desafíos relevantes para la comunicación científica están especialmente asociados a ciertas zonas de este espacio. En base al marco propuesto, también abordamos posibles estrategias y desarrollos en el ámbito de la comunicación científica.

1. Introduction

The idea that science communication can be studied with the tools of science itself (e.g., Fischhoff & Scheufele, 2013) is plausible. After all, we can apply the main elements of the scientific approach (developing hypotheses and critically evaluating them on the basis of controlled data) to the most diverse phenomena —why not to science communication? Indeed, results obtained in established scientific fields (cognitive psychology, just to mention one clear example) can already be integrated in analyses of science communication (Mercier, 2020). So it makes sense to

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think that there is specific knowledge concerning science communication, with no convincing alternative to systematic, rational, and empirically testable research, i.e., scientific research, to obtain and consolidate such knowledge.

To apply scientific methods to the study of science communication, the science of science communication adopts an empirical approach towards issues such as understanding audiences, designing messages, and evaluating communication strategies. In this sense, one of the central aims of the science of science communication is to address the so-called "science communication paradox" (Kahan, 2015): although human societies have significantly expanded their understanding of the natural and social world, there is little consensus on the scope of their collective knowledge. Other major challenges are related with new media formats, emergent research topics, and polarised political environments (Akin, 2017). The science of science communication is meant to be distinct from research on other forms of communication, e.g., political communication, because of the privileged rhetorical status of science communication and, consequently, the specific standards and norms to be met (Jamieson, 2017).

It should be aknowledged, however, that this remains an emergent field with contributions from a variety of potentially diverging perspectives (Kahan *et al.*, 2017). Under these circumstances, a rather basic effort of organization of the phenomena may be worthwhile. The main aim of this paper goes in this direction: our goal is to outline a scheme for classifying diverse kinds and modes of science communication and to explore the potential of such scheme. In developing our proposal, we will keep the use of theoretical assumptions and tools to a minimum, adopting a descriptive approach potentially providing a basis for a comparative and independent evaluation and/or integration of different theoretical and practical approaches. Our discussion will especially illuminate and partly systematise the diversity of science communication, introducing a framework for assessing an array of scenarios, problems, and strategies.

The structure of the paper is as follows. Section 2 introduces the issue of the diversity of science communication settings and activities. Section 3 discusses three relevant dimensions of science communication. It outlines a three-dimensional space regarding which particular communication scenarios can be located. Section 4 illustrates the three-dimensional space of science communication by means of particular cases. Section 5 discusses important challenges faced by science communication. We argue that some difficulties are particularly associated with certain areas of the spatial representation outlined. Section 6, based on the proposed framework, addresses potential strategies and developments in science communication. Finally, section 7 concludes.

2. *The diversity of science communication*

Science communication is a very broad field. According to the influential characterisation proposed by Burns *et al.* (2003), science communication encompasses the diverse skills, media, activities, and dialogues that aim to produce awareness, enjoyment, interest, opinions, or understanding of science in a certain audience. The target audience of science communication can be (a group of) media, corporations, policy-makers, or the general public.[1] Furthermore, science communication can concern virtually any topic related with science or technology. Still, science communication can be demarcated as usually guided by some general rules including to be ethical, to respect the factual truth, to not omit viable options, and to declare possible conflicts of interest (Jucan & Jucan, 2014).

Science journalism and documentaries that address topics in the natural sciences (e.g., astronomy) are often considered paradigmatic examples of science communication. Certainly, the main role of those media contents, which are

1 In this paper, we will focus on cross-sectoral communication between scientific communities and other segments of society. Nonetheless, science communication may also involve interactions within or between scientific communities (e.g., scientific conferences), as well as interactions between laypeople (e.g., citizen meetings about scientific issues) (Trench & Bucchi, 2010).

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targeted to the general public, is to increase awareness and understanding of important scientific facts. Nevertheless, science communication arguably is involved in many other scenarios such as medical consultation, science and technology museums, public-health campaigns, and even science fiction films. These also partly aim at producing certain personal responses towards science in their audience (enjoyment is surely one example).

In a pioneering study, the UK Office of Science and Technology and the Wellcome Trust (2001) reviewed science communication activities in Britain. The study included nine in-depth face-to-face and fifteen telephone interviews with key players in science communication. Moreover, forty-four web questionnaires and thirty-five telephone interviews were carried out. According to the study, science communication activities in Britain diverge in important aspects such as the objective of the activity, how innovative it is perceived to be, and the geographic area of influence. Those activities include, among others, open days, science clubs, and government-commissioned reports. In the last decades, the diversity of science communication has arguably increased even further. The development of new technologies such as smartphones and the popularisation of social networks such as Facebook or Instagram have given rise to new forms of interaction between science communicators and audiences. Consider for instance YouTube. YouTube has become an important platform for sharing both user-created and professionally generated content about science (Allgaier, 2020). This website allows for a direct, immediate, and interactive form of science communication. Communicators can create and upload their videos autonomously and even interact with the audience in real time.

Nonetheless, the diversity of science communication and the divergences between particular communicative scenarios arguably deserve more attention than is currently acknowledged from scientists, science communicators, and theorists. Lack of attention may be also related to so-called *deficit approach* to science communication. Despite sustained criticism among specialists, many scientists and science communicators still embrace core elements of the deficit approach and tend to identify science communication straight away with the closure of a knowledge gap in the audience (Besley & Tanner, 2011; Cortassa, 2016; Davies, 2008; Suldovsky, 2016).[2] This approach, however, does tend to overlook particularities of the diverse science communication scenarios and to invite a one-size-fits-all approach to practice.

The deficit approach is based on the *deficit model* of the public understanding of science (Ahteensuu, 2012; Bubela *et al.*, 2009; Bucchi & Trench, 2014; Burns *et al.*, 2003). According to this model, novices usually have inadequate or incomplete knowledge or understanding of science. Such ignorance is considered to be the basis of most negative attitudes towards science and technology (e.g., scientific scepticism). For advocates of the deficit approach, the main role of science communication is to provide accurate information about science and fill the deficit in knowledge. It is considered that such (one-way) transfer of information is the fundamental tool for achieving scientific literacy and, as a consequence, public support of science.[3]

In the deficit framework, the diversity of science communication is indeed typically overlooked. It is assumed that both the challenge faced and the adequate intervention are virtually the same in all cases and differences among di-

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2 In the (academic) debate on science communication, several concerns have been raised against the deficit approach. Science communication scholars have argued that this approach is overly simplistic, empirically inadequate, and largely ineffective (Bubela *et al.*, 2009; Bucchi & Trench, 2014; Nisbet & Mooney, 2007).

3 In recent decades, various alternative approaches to science communication have been proposed. Among these, the communication of scientific consensus has garnered particular attention (Bayes *et al.*, 2023). It has been suggested that consensus messages influence the perceived consensus and, consequently, laypeople's beliefs and attitudes. Existing evidence supports the role of perceived consensus in the formation and acceptance of beliefs (Mercier, 2020). Furthermore, in the context of climate change communication, several empirical studies have found a positive effect of consensus messaging on the acceptance of climate change and support for public action (van der Linden *et al.*, 2015, 2019). However, concerns have also been raised regarding the potential side effects of consensus messages (Chinn & Hart, 2023; Ma *et al.,* 2019). Under certain conditions (e.g., conflicting prior beliefs), such messages may be perceived as manipulative, provoke reactance, and even backfire.

verse contexts of science communication elude thorough consideration. In particular, little attention is paid to the particularities of the audience, the source of information, and the scientific domain. The deficit approach appears to essentially presuppose that the public is homogeneous regarding the relevant aspects (Nisbet & Scheufele, 2009; Simis *et al.*, 2016). It is considered that novices lack important scientific knowledge and that informing them will successfully fill the gap and lead to positive attitudes towards science. Peculiarities related with audience's concerns, values, political views, and pre-existing beliefs are also typically neglected. Also, the deficit approach does not take into account the particular sources involved in science communication and the way in which they relate to the audience. The deficit model focuses on the content of the message (i.e., the relevant scientific information) and hardly takes into account contextual aspects of the communicative process. Finally, in the deficit framework, differences between scientific domains are regarded as irrelevant with virtually no impact on how science communication generally works. In all cases, the main problem is related with a knowledge deficit and should be addressed by providing the missing piece of scientific information.

Although science communication scholars often claim that the deficit approach has been abandoned, its prevalence among scientists and science communicators has been highlighted by different empirical studies. By means of several group interviews and discussions, Davies (2008) examined scientists' ideas on science communication. She highlights the influence of the deficit framework and argues that science communication is widely viewed as a one-way transfer of scientific information. Besley and Tanner (2011) interviewed science communication scholars about their views on scientists and their communicative training. According to their study, scholars broadly agree that the deficit approach remains prevalent among scientists.

There are several factors that seem to contribute to the persistence of the deficit approach. Suldovsky (2016) argues that there are strong links between widespread views of fundamental aspects of science (e.g., scientific knowledge) and science communication (e.g., purpose), and the deficit approach. For example, it is often considered that science communication's main role is to promote science within the public sphere. The communicative relationship between science and the public is thus often understood as unidirectional: science contributes to improve society, but societal phenomena and determinants play no role in science and scientific understanding. Simis *et al.* (2016) also argue that there are practical aspects that foster the persistence of the deficit approach. They argue that one crucial aspect is scientists' (lack of) training. Scientists rarely have formal training and understanding of public communication. They are not taught specifically about how laypeople form their beliefs about science and how to effectively communicate with them. The authors also consider another important factor, namely that the deficit approach leads to easy-to-implement policy designs. According to this approach, policy interventions simply have to address ignorance and promote scientific literacy.

The diversity of science communication is sometimes overlooked even by scholars of science communication among which the deficit model is widely rejected. Many analyses of science communication, although aiming at general conclusions, focus exclusively on a particular kind of science communication practices (Bubela *et al.*, 2009). Special attention is typically given to print media and science journalism. Furthermore, studies on science communication usually address the communication of scientific research and do not pay attention to the particularities of the communication of technological developments (Trench & Bucchi, 2010). Finally, science communication scholars usually focus on the effects of one-time exposure to a single message, which is studied in isolation, and pay little attention to continued exposure and its implications (So *et al.*, 2017).

Overlooking the diversity of science communication is not harmless. Not only does it lead to descriptively inadequate accounts of science communication, but it can also have practical consequences. The challenges faced by science communication and the efficacy of interventions usually depend on the particularities of the communicative context. Not paying attention to the latter may result in ineffective (or even harmful) interventions. Consider, for instance, the audience. Although science communicators care about the audience and for the message to be understood, relevant features of the target population may be overlooked. Previous knowledge about certain scientific issue varies greatly depending on aspects such as interests, social background, and domain. That means, for example, that the previous knowledge of the audience is likely to vary from one communication context to another. This previous knowledge, however, may have a significant influence in the effect of certain science-related messages (Bruine de Bruin & Bostrom, 2013; Fischhoff, 2013). Indeed, humans are more likely to accept those messages that suit their pre-existing views. For example, in two experiments about science communication on carbon-nanotubes and genetically modified foods, Druckman and Bolsen (2011) found that individuals' impressions and reactions to new factual information were biased by their previous views on the topic. Participants in the experiment tended to perceive factual information consistent with their initial opinion of the technology as stronger. Moreover, they also tended to perceive neutral factual information as consistent with their prior opinion. When the previous knowledge of the audience is overlooked, one can see even negative side effects taking place. For example, messages that the audience perceives as inaccurate, oversimplified, or repeating well-known facts may sometimes erode the trust in science communicators (Fischhoff, 2013).

In sum, science communication is a broad area including diverse activities such as science journalism, medical consultation, and operating museums. Nonetheless, the diversity of science communication tends to be overlooked by scientists, science communicators, and even science communication scholars. In some cases, this lack of attention may be related with the (unabated prevalence of the) deficit approach to science communication.

3. Three dimensions of science communication

Considering the breadth of science communication, it is essential to identify, analyse, and categorise the diverse scenarios that may emerge. Such categorisations can enrich theoretical discussions about science communication and also provide a practical framework for communicators. This framework could assist in tasks like selection of strategies, development of materials, and anticipation of potential challenges.

In the recent literature, we find several attempts to systematise science communication (Desmond, 2024; Elliott, 2017; Sánchez-Mora, 2016). Elliott (2017) focuses on engagement activities, i.e., interactions among people or institutions to exchange views, highlight problems, or evaluate proposals. Based on the entities involved and the way of interaction, he distinguishes four main forms of engagement: (1) bottom-up engagement between community groups and researchers, (2) top-down engagement exercises to elicit public participation, (3) interdisciplinary engagement between scholars, and (4) engagement with laws, policies, and institutions that influence scientific research. This categorisation aims to highlight the diverse ways in which values may influence science. On the other hand, Desmond (2024) focuses on expert communication and distinguishes it from other forms of science communication. Expert communication is perceived as authoritative, conveys assertions about the state-of-the-art, and informs decision-making about possible courses of action. Regarding expert communication, Desmond outlines a typology based on the priority given to transparency and actionability. He identifies and characterises, among others, persuasive communication, paternalistic communication, and manipulative communication.

In this section, we introduce a new framework for assessing and characterising particular scenarios of science communication. We take our current proposal as a complement and an extension of others available, with a focus on three relevant dimensions: size of the audience, frequency of interaction, and decision-making relevance. As it has been noted, in science communication, target audiences can diverge for several aspects, e.g., social role. One crucial aspect which may be overlooked is the *size of the audience*. The size of the audience can range from one person to a large number of people. In science communication contexts such as medical consultation or scientific advising, the audience is often small. It is usually limited to one patient (and perhaps some member of their family), in the first case, or some decision-makers in the second case. In public lectures, however, the audience often includes hundreds of people. In those lectures, renowned scientists usually present major research findings to a large group of laypeople. In some contexts, the audience may be even larger. For instance, public health campaigns are usually targeted to the whole population of a region. In fact, given the recent technological developments and the popularisation of social networks, the potential audience of a science-related message can be millions of people worldwide. This is the case, for example, of science-based films and YouTube videos.

The second dimension is the *frequency of interaction* between the communicator and the audience. The recurrence of the communicative interaction between science communicators and audiences can vary greatly. It can range from one unique interaction to regular interactions every few days. Those regular meetings may even span a long period of time. In the context of temporary exhibitions in science and technology museums, for example, the frequency of interaction with the audience is very low. People usually visit a particular exhibition just once before it is dismantled or moved to another venue. However, in other scenarios, there is a high frequency of interaction with the audience. For example, some science communicators become public celebrities and frequently address a loyal audience of laypeople from diverse platforms. This is the case of public figures in science communication such as Carl Sagan, Neil deGrasse Tyson, or Richard Dawkins.

The third dimension is the *decision-making relevance* of the topic addressed. Science communication can be about any topic related with science or technology and the relevance of those topics for decisions of concern of the audience varies greatly. Some scientific issues are connected to important health, economic, or political decisions, while others are highly disconnected from the audience's everyday life and decisions. For example, as popular as it is, science dissemination about astronomy has typically little decision-making relevance for laypeople. In this context, science communication mainly aims at satisfying an intellectual curiosity and increase awareness about objects and phenomena on a cosmic scale. On the other hand, communication on nutrition may have a high decision-making relevance. In this context, the aim of science communication is easily related to dietary habits in the target population. Differences regarding decision-making relevance may be found even among communication activities of the same type. Public lectures, for instance, address topics with diverse degrees of relevance, from mental health to dinosaurs' extinction.

The decision-making relevance of a particular topic may change from one audience to another. For instance, information about the heat conductivity of a newly discovered inorganic material may have little decision-making relevance for the general public, but be relevant, say, for decision-makers in charge of distributing public funds for research or making investment choices. Consequently, the decision-making relevance of a topic should be considered in relation to a certain audience.

One can usefully integrate these three dimensions in a three-dimensional space of science communication. This space can be represented with a figure like the following.

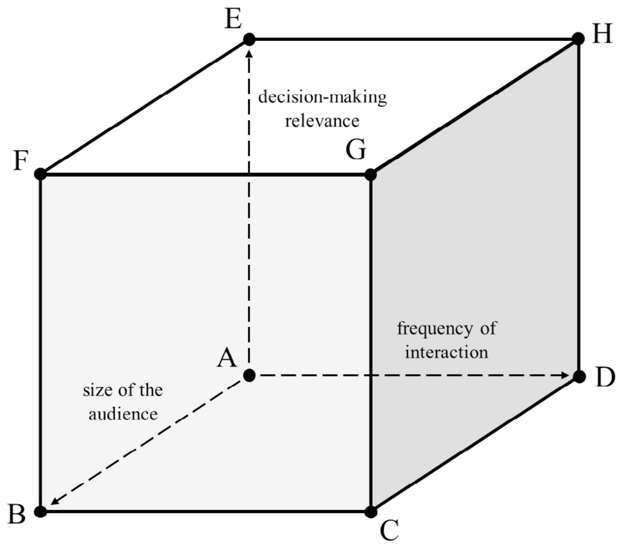

Fig 1

Three dimensions of science communication

Summing up, science communication includes very diverse cases. Particular scenarios can be characterised regarding the size of the audience, the frequency of interaction, and the decision-making relevance. Those three dimensions build up a three-dimensional space of science communication in which we can locate particular cases. We consider that the proposed dimensions and the resulting framework have important strengths. First, our proposal encompasses many forms of science communication. Any communication from scientific communities to other segments of the society can be situated with respect to the proposed dimensions, while other approaches tend to focus on a particular kind of scenarios (see, for instance, Desmond, 2024). Second, the dimensions considered can often be assessed in advance. Even before a communicative interaction has taken place, science communicators can assess those parameters and roughly locate the communicative scenario in the three-dimensional space. Third, situating a scenario with respect to these dimensions helps to anticipate possible challenges and to assess available strategies in science communication. (We will explore this last aspect in sections 5 and 6.)

4. *Particular scenarios of science communication*

In order to illustrate diverse areas of the three-dimensional space of science communication, we are going to characterise and locate in this space some paradigmatic scenarios of science communication.

Let us consider, in the first place, science communication in clinical practice. In specialised medical consultation, interactions between doctors and patients are usually situated in the area close to vertex E. The interlocutor of the communicator (doctor) is a single individual (patient) and perhaps their family. Furthermore, there is a low frequency of interaction. The doctor and the patient usually just meet once or few times to talk about the issue of the condition detected and the appropriate treatment.[4] Finally, the scientific content involved is normally quite relevant for patients' decision-making: the doctor provides information to guide decisions directly related to health.

An illustration of this kind of scenario is provided by early-diagnosed prostate cancer (Chen *et al.*, 2017). In this context, the urologist must inform the patient about the condition and the feasible (surgical and non-surgical) interventions, among which one has to choose. The audience of the message is typically a particular patient. Not only is the message targeted to the patient, but it is also tailored to them (or at least it should be; see Tentori *et al.* 2018). The doctor and the patient only meet a few times after the diagnosis to discuss the clinical situation and the available interventions (indeed, the time frame for decision is often substantially limited). Moreover, the issue addressed has a high decision-making relevance for the patient. After the communicative interaction, the patient is supposed to endorse an informed choice among the available courses of action.

Secondly, consider science communication in public health. In public health campaigns, interactions between communicators and the general public are usually in the area close to vertex F. The audience of the communicator is a large group of people (e.g., the whole adult population of a country). Furthermore, there is a low frequency of interaction. People are normally addressed by the message of a particular campaign during a limited period of time. Finally, the topic at issue is usually relevant for decision-making. Public health campaigns aim to inform citizens and guide their behaviour in health-related areas.

In order to illustrate this kind of scenario, consider vaccination against seasonal influenza. Health communication campaigns are crucial to inform about and promote vaccination (Rowlands, 2014). In the context of seasonal influenza, where communication campaigns are usually funded by national or regional health agencies, the target audi-

[4] There are some cases in which specialised doctors and patients meet regularly (e.g., medically supervised diets). In those cases, the context of science communication may be closer to vertex H. Note, however, that only a fraction of the physician-patient interaction concerns the communication of scientific content.

ence of the message is the whole population of a state or a region. Moreover, citizens are addressed by the messages of the campaign for a limited period of time. In particular, they are involved mainly during the weeks preceding the expected annual outbreak of influenza infections. The topic at issue has significant decision-making relevance for the citizens. On the basis of the received information and their pre-existing beliefs, they have to decide whether to get vaccinated or not.

As a final example, let us discuss podcast-based science communication about, say, astronomy. In the context of dissemination podcasting about astronomy, interactions between science communicators and novices are usually in the area close to vertex C. The (potential) audience of the message is a large group of people: podcasts are usually available in open platforms accessible to everyone. Often there is a high frequency of interaction between the communicator and the audience (most podcasts release episodes on a regular basis, e.g., weekly). Also, the issue addressed has a low decision-making relevance for the audience: in their everyday life, their decisions are not meant to be much influenced by the information received about astronomic phenomena and discoveries.

A specific and well-known example of this kind of scenario is the podcast *StarTalk Radio* hosted by Neil deGrasse Tyson. *StarTalk Radio* aims to divulge about astronomy and physics. The podcast is available in several platforms such as Apple Podcasts, Google Play Music, SoundCloud, Spotify, Stitcher, and TuneIn. Furthermore, it is complemented with videos available on YouTube. As a consequence, the potential audience of this podcast amounts to millions of people. There is also a high frequency of interaction with the audience. A new audio episode is released every week. Furthermore, the audience can interact with the team of the podcast by means of their accounts in social media such as Twitter, YouTube, Instagram, Facebook, SnapChat, and TikTok. Some episodes are even devoted to answer questions by the audience. Nonetheless, most of the issues addressed in the podcast are not relevant for audience's decision-making. It usually addresses topics such as the nature of black holes, space exploration, and the Big Bang.

To sum up, representative cases of science communication differ regarding the dimensions considered and, consequently, their location in the three-dimensional space. Medical advising, public health communication, and podcast-based science communication about astronomy provide illustrations of how diverse activities are related.

5. *Challenges in science communication*

In the diverse areas of the space of science communication, different challenges are typically faced. By placing certain activities and initiatives in this space, one will be able to anticipate some of the difficulties to be handled.

5.1. Challenges related with size

As it has been noted (see section 2), recipients of science communication may diverge in many relevant aspects, e.g., political views, education, social background, etc. Moreover, as the target population increases in size, the audience often tends to become more heterogeneous concerning these aspects.[5] For instance, if we direct our message to the population of a city rather than that of a neighbourhood, one can plausibly expect greater divergences in prior scientific knowledge. This audience heterogeneity may result in the message having different effects on different members of the target population. Let us discuss this in some detail.

[5] From a logical standpoint, population size and heterogeneity are independent factors. Surely enough, an increase in size does not necessarily entail an increase in heterogeneity. We take the dependence of heterogeneity on population size as a tendency which will be modulated by other factors and is likely to emerge in at least some common circumstances. As a consequence, the illustrations that we discuss here are meant to apply on the provisos that such ordinary circumstances hold. (We thank an anonymous reviewer for prompting this remark.)

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Individuals assess the messages that they receive guided by mechanisms of "open vigilance" (Mercier, 2020). Some of these mechanisms assess the content of the message, such as plausibility checking and reasoning. In the light of pre-existing beliefs and inferential mechanisms, the information communicated is evaluated. For example, people may assess how strong the arguments in support of a certain suggestion or claim are. Other mechanisms of open vigilance focus on the source of the message. Those mechanisms consider the past performance of the source, its access to information, its relative diligence, and the agreement with other sources. For instance, when the source has been consistently right in its claims in a certain domain, people are more likely to accept its messages in that domain.

Nevertheless, the performance and reliability of mechanisms of open vigilance is not constant among individuals and populations (Pérez-González & and Jiménez-Buedo, 2023). Their performance is influenced by the properties and particularities of the individual recipient, which, as it has been noted, may vary a lot. Consider, for example the mechanism of reasoning and how it involves the assessment of arguments. Individuals assess the arguments in support of a claim on the basis of their pre-existing knowledge about inferential mechanisms and processes. However, this knowledge may vary a lot from one individual to another. It would depend, for instance, on education and training.

Those divergences among individuals (and assessments) can be found in public understanding of science. Since the 1950s, the US National Science Foundation collects data on Americans public attitudes and understanding about science and technology. Based on the 2016 survey, Besley (2018) uses latent profile analysis to identify homogeneous subgroups regarding views about science and technology. For that purpose, three kinds of variables are taken into account: demographic variables, ideology variables, and attitude variables. Demographic variables include variables related to scientific background (e.g., general education level). The study identified six different subgroups: disengaged, worried, cautious conservatives, moderate optimistic, liberal sciencephiles, and conservative sciencephiles. Those subgroups, each of which is highly homogeneous, differ from each other regarding the variables under consideration. Similar studies on population segmentations are available for other countries too (Schäfer *et al.*, 2018).

The assessment, evaluation, and acceptance of certain science-related message may diverge from one individual to another. When a population is large and heterogeneous, those divergences are expected among members of the population itself. As a consequence, a particular message would have different effects in different members of the population. For example, a counterintuitive claim supported by strong arguments is more likely to be accepted by individuals with deep knowledge about inferential processes, whose approach to reasoning is reliable, than by individuals with limited knowledge and access to those processes.

We would finally like to highlight that heterogeneity poses a major challenge to the development and selection of science messages and campaigns (Pérez-González & and Jiménez-Buedo, 2023). When the target population is large and (potentially) heterogeneous, messages are likely to have unequal effects among members of the population and involve trade-offs (Besley, 2018). For example, simple but inaccurate messages can be more effective with more people but, at the same time, may be perceived as misleading and increase mistrust among informed individuals. In order to develop and select the adequate message, it is crucial to anticipate their effects in the target population, but such anticipation may sometimes be challenging. The net effect of a particular message depends on the composition of the population and the properties of its members. However, when there is a limited access to the population of interest (e.g., low frequency of interaction), detailed information about those aspects may be difficult to gather.

Audience size may also affect the chances of getting reliable feedback in the communication process. According to the research, a construal of science communication as an exchange with the audience is not widely supported in practice. While science communication trainers do value interaction with the audience, they also acknowledge that it is rarely practiced (Yuan *et al.*, 2017). When scientific content must be conveyed, however, one would ideally want to check how the message is being received and managed. In fact, such feedback information may be extremely valuable for a number of reasons: it signals potential sources of misunderstanding, it suggests directions in which a more thorough, careful, and extensive treatment may be needed, and it reveals whether and how the content interacts with non-epistemic attitudes, perhaps triggering emotional reactions or partly trespassing into the domain of political debate or ethical value. Indeed, the need to communicate with reduced opportunities to assess and understand the effects of messages on the audience (largely due to the emergency conditions) was arguably one of the reasons why the COVID-19 outbreak was a formidable stress test for science communication (see, e.g., Pollett & Rivers, 2020).

Getting useful feedback from the target audience of scientific communication does not necessarily require formal methods of data collection. Nonetheless, research suggests that it turns out to be a remarkably demanding task even under relatively favourable conditions, such as a clinical setting where the expert (physician) can interact directly with a single layperson (patient) (Back *et al.*, 2019; also see Tentori *et al.*, 2018). When the size of the target audience increases further, it is crucial to keep in mind some important conditions for success: the feedback information should ideally be representative and informative, timely, and appropriately interpreted.

At first sight, it may seem obvious that one can get effective feedback in the service of scientific communication with large audiences through the powerful technological platforms available nowadays. This may indeed be straightforward as concerns the timeliness of reactions from the audience: in this respect, scientific communication through social networks and similar channels is surely disruptive in comparison to more traditional media. But such advantage does not necessarily extends to other relevant features for the quality of the interaction. To begin with, more opinionated reactions (be they supportive or confrontational) may easily be overrepresented or overweighted, to the detriment of representativeness and informativeness about the communication process itself. Moreover, when feedback is recorded and shared (as it often is in online platforms), additional complications arise. Shared feedback may significantly modulate the impact of the original message. For instance, Winter and Krämer (2016) observed a tendency by readers to be distinctively affected in various ways by adversarial reactions in the assessment of blog articles on science-related content (the dangers of violent video-games). No less important, shared feedback across large audiences may foster a strong tension for the communication agency, namely a tension between the goal of achieving better understanding on how the scientific content gets across and the legitimate but separate goal of gaining popularity to extend the reach of the message.

In summary, when the size of the audience is large, certain difficulties in science communication can be expected. In particular, audience may be heterogeneous and differ in their epistemic attitudes. Moreover, it is complicated to obtain reliable feedback even when modern technological platforms are used.

5.2. Challenges related with frequency

In scenarios with high frequency of interaction, science communication is often related with repetition of similar messages. Consider, for example, campaigns on tobacco consumption, obesity, safe sex, or global warming. The main aim of the frequent interaction and repetition is to increase acceptance of the message and, in some cases, produce behavioural changes. It is assumed that more message exposure is better and more effective. Nevertheless, overexposure to a particular message or to a set of similar messages may result in unintended side effects. A particularly relevant potential side effect is message fatigue (Kim & So, 2018; So, 2022; So *et al.*, 2017).

Message fatigue is characterised as “an aversive motivational state of being exhausted and bored by overexposure to similar, redundant messages over an extended period of time” (So *et al.*, 2017, p. 10). It is usually associated with perceived overexposure, perceived redundancy, exhaustion, and tedium. Message fatigue may be fuelled not only by mediated communication (e.g., media coverage), but also by interpersonal communication (e.g., casual conversations). When a scientific topic becomes pervasive in interpersonal relationships, message fatigue is more likely to appear.

Message fatigue tends to reduce message acceptance and adoption of advocated behaviours (Kim & So, 2018; So, 2022; So *et al.*, 2017). This effect is mediated by both active and passive resistance to additional messages (Kim & So, 2018; So, 2022). Active resistance is related with reactance. Individuals of the audience oppose the message and argue against it. This kind of resistance is considered to be associated with those cases where a specific message source is deemed accountable for message overexposure. Passive resistance is related with disengagement and inattention. Members of the audience simply withdraw their attention for messages perceived as redundant. This kind of resistance is considered to be associated with scenarios where the message environment (and not a particular source) is perceived as responsible for overexposure.

Message fatigue is particularly relevant and worrisome in the context of anti-tobacco messages and campaigns (So, 2022; So & Popova, 2018). In the last five decades, a large volume of messages highlighting the harmful effects of tobacco consumption has been released. In a recent study, So (2022) discusses the effects of overfamiliar antitobacco messages focusing on negative physical health consequences (e.g., warning labels on cigarette packages). The study shows that conventional anti-tobacco messages, which focus on physical health consequences portrayed in a loss frame, induce message fatigue. Those messages are also found to be associated with higher levels of active and passive resistance and, as a result, a reduction in persuasive effects on quitting smoking.

Fatigue for a recurrent message is only one potential challenge when communication happens on a regular basis. Another one, which is no less important, may actually arise from the opposite phenomenon, namely a difficulty to maintain consistency. In certain circumstances, the task of providing scientifically accurate reports over time may generate a pattern of apparently diverging messages, involving a risk that public trust in the source is weakened and perhaps confusion emerges. Here again, important illustrations have emerged during the recent COVID-19 global crisis, when communication of scientific content on a regular (in fact daily) basis has been mandatory.

One potential hurdle for consistent communication over time is the temporal overlapping of forecasts and regulatory interventions. In the COVID-19 pandemic, for instance, the effectiveness of physical distancing measures has in many cases 'disproved' the worst epidemiological forecasts. In a case like this, a specific effort of clarification is in order for the correct implication (namely, that regulations turned out to have an effect) to prevail on misguided ones (e.g., that the forecasts were actually alarmist). Moreover, from the very beginning of the pandemic, experts had to devote many efforts to refute unfounded or distorted interpretations, even when it was already foreseeable that the scientific understanding of events would also evolve rapidly, as it invariably did (Scheufele *et al.*, 2021). But to be informed about science "in the making", when the understanding of phenomena develops quickly through widespread uncertainty, may be disorienting and confusing unless citizens are enabled to monitor, reconstruct, and interpret the (real or apparent) 'turnarounds' that cutting-edge research may deliver until stable clairity and consensus are finally achieved.

The prospects of science and technology are constantly evolving. This is particularly clear in emerging fields (e.g., artificial intelligence) and in contexts more affected by human behavior (e.g., economics, epidemiology). When science communication is limited to one or very few interactions, it usually focusses on a synchronic view, typically aiming at an accurate outlook at a given moment. But even if a message is accurate at the time it is delivered, it may soon require substantial adjustment or revision. So in a diachronic perspective, episodes of communication should be able to integrate and convey due consideration of the dynamic nature of science.

To sum up, when there is a high frequency of interaction, some specific problems are likely to emerge in science communication along with corresponding opportunities. In those cases in which messages remain similar over time, message fatigue can reduce its acceptance. Furthermore, given the changing nature of science, maintaining consistency among messages may require special effort.

5.3. Challenges related with decision-making relevance

In contemporary science communication, a particularly pressing challenge is science denialism. Science denialism is a specific form of a pseudoscientific attitude (Hansson, 2017). It consists in the systematic rejection of scientifically well-established results or claims on which a scientific consensus exists (Diethelm & McKee, 2009; Hansson, 2017). Science denialism is usually associated with strategies such as creating fake controversies, misrepresenting scientific claims, introducing deviant criteria of acceptance, and cherry-picking of data. Some well-known examples of science denialism are climate change denialism, evolution denialism, and holocaust denialism. Unlike pseudotheory promotion (e.g., homeopathy), science denialism does not focus on the promotion of a specific pseudoscientific theory. Nevertheless, in order to increase controversy and undermine the target claim, denialists usually rely on alternative theories (e.g., intelligent design) and spread misinformation.

Science denialism is usually motivated by people's worldview or (political or economic) interests (Lewandowsky *et al.*, 2016; Lewandowsky & Oberauer, 2016). On the one hand, people tend to reject scientific findings and claims that challenge their core beliefs and worldviews: consider, for example, rejection of biological evolution by certain Protestant groups. On the other hand, people tend to reject scientific findings or claims that threaten their economic or political interests. In an empirical study, Blank and Shaw (2015) assessed how deference to science is influenced by partisanship, ideology, and religious beliefs. For that study, 2000 online interviews to American registered voters were conducted. The study found that both ideology and religious beliefs influence attitudes towards scientific expertise. For example, biblical literalism correlated with low levels of confidence in science. Nonetheless, relevant variations were identified across issue domains. On issues that touched on political matters, for instance (e.g., health insurance), willingness to defer to scientific expertise decreased overall.

Denialism may become particularly concerning when the affected group is well organised (e.g., tobacco manufacturers, see (Proctor, 2011)). In empirical studies, organised denialism has been shown to have the potential to significantly influence the public understanding of science. McCright *et al.* (2016) studied the influence of diverse frames on communication about anthropogenic climate change. They considered both positive frames for increasing concern (e.g., national security frame) and a denial counter-frame. The study found that the denial counter-frame significantly reduced participants' beliefs in the reality of climate change, their awareness of climate change consequences, and their support for greenhouse gas emissions reductions. Moreover, the denial frame had a stronger influence on conservatives, who initially reported weaker beliefs about the reality and impact of climate change, than on moderates and liberals.

In contexts where science communication has high decision-making relevance, there will be a tendency for scientific content to interact more closely with people's values and preferences, and science denialism may arise more easily.[6] This tendency is further accentuated when the affected group is well-organised. In order to illustrate the threat of motivated denialism, let us consider the public debate about climate change. This debate has a high decision-making relevance for both policy-makers and citizens. Policy-makers have to make decisions on fuel taxation, green energy, sustainable materials, etc. At the same time, in their everyday life, citizens make certain elections regarding energy consumption. In this public debate, organised denialism has arisen (Brulle, 2014; Dunlap & McCright, 2011). The organised climate change counter movement (CCCM) has contributed to public misunderstanding of climate change and governments' lack of legislative action. In this, sense, for instance, CCCM was crucial for the decision of the United States senate of not ratifying the Kyoto Protocol in 1997 (McCright & Dunlap, 2003). The conservative movement interpreted concerns over global warming as a menace to American industry, prosperity, and lifestyle. Consequently, conservative think tanks (e.g., Heritage Foundation) challenged the legitimacy of global warming as a problem by means of diverse strategic actions. Those actions included producing advertisements, appearing on television programs, and taking part in Congressional hearings. Moreover, they regularly collaborated with American

[6] Here again, the connection is of course contingent, and specific counterexamples are expected. Communicating about the latest research in fluid dynamics to aerospace engineers may be construed as having high decision-making relevance for the audience, but denialism can be safely ruled out in this setting. And conversely, denialism may happen to target bits of scientific content even when practical impact appears to be very limited. The tendency we mention in our discussion is mediated by a stronger interaction with possibly divergent personal values and preferences, and such proviso should be kept in mind. We thank an anonymous reviewer for prompting these cautionary clarifications.

climate change sceptics. All these efforts eventually resulted in the redefinition of global warming as non-problematic. That redefinition influenced in the policy arena and contributed to the no ratification of the Kyoto Protocol.

When science communication involves topics directly relevant to choices of social or personal interest, it is also crucial to remember that expertise does not automatically extend from the former to the latter. One crucial aspect of this issue has to do with a fact / value divide, and is perhaps easier to acknowledge: there is always an irreducible logical gap between an informed understanding of the scientific and technical dimension of a problem and an assessment of what we should do as a society and as individuals (Varma, 2021). A more subtle and additional complication is *intra*scientific, however: it involves the boundaries between distinct disciplines (especially natural *vs*. behavioral sciences) as they relate to a single topic of interest, such as nuclear energy or vaccination. To avoid distortions, it is not enough that experts are personally and subjectively aware of these gaps (which may also not be guaranteed). When the decision-making relevance of scientific content grows, it is the manner of communication itself that should make the gaps clear to the audience.

Consider recent philosophical discussions on *epistemic trespassing* (Ballantyne, 2019) or *expert trespassing testimony* (Gerken, 2018). Epistemic trespassing may occur when an expert pass judgment on questions in fields where they lack expertise. In typical cases, a significant subset of the audience is likely to consider that the judgment refers to their field of expertise. Expert trespassing testimony is usually both epistemologically problematic and morally problematic. It can be seen as a violation of a basic maxim of pertinence in the epistemology of expertise, whereby good experts give judgment within their field of competence and do not judge without qualifications on matters outside the scope of their expertise (see Martini, 2019). Expert trespassing testimony normally gives rise to epistemically inhospitable circumstances, i.e., circumstances in which audience's ability to form truth-conductive believes is undermined (Gerken, 2018). Note that, when a layperson forms a belief out of trust in a source in the corresponding domain of expertise, the process will typically generate a *justified* belief. If epistemic trespassing occurs, however, the layperson may easily end up with a similar degree of confidence in their belief, but without the benefit of a comparably strong degree of justification (DiPaolo, 2022). The science and technology of nuclear energy for civil uses is distict from knowledge about its economic or societal sustainability, for instance, yet a science communicator targeting the former may find themselves willing or urged to address the latter. A similar situation may arise with someone versed in the science of vaccine efficacy when it comes to the plausible consequences of alternative approaches in vaccination policy. In such circumstances, epistemic trespassing may well be non-malicious and even inadvertent, but it is worrisome nonetheless. In fact, epistemic trespassing should be considered a specific risk for science communication at the top area of our figure above.

Summing up, when addressed topics have high decision-making relevance, science communication tend to face certain difficulties. In those cases, motivated science denialism is likely to emerge. Moreover, scientific advice may encounter diverse problems related with expertise.

6. From challenges to prospects

So far, we have put forward a tentative map of diverse science communication settings and activities, with a focus on three selected dimensions. However rudimentary, this mapping exercise yielded a benefit of systematization: as it turns out, one can subsume and understand a significant variety of cases as belonging to distinct areas of our parameter space and make sense of how they all involve the communication of scientific content although in different terms. Moreover, we have suggested that variation along each of our key dimensions modulates the kind of challenges that will predictably become more pressing for science communication to prove effective under the relevant circumstances. Here we want to pursue a more constructive outlook and consider how our approach can be helpful for discussions about strategies and developments to improve science communication.

To the extent that the diverse landscape of science communication becomes at least partly organized, a clearer picture can emerge as concerns certain tools that are potentially effective but also controversial. *Framing* is an interesting example. It is a long established fact in behavioural science that humans' understanding of information can vary in a systematic way depending on how such information is framed, namely, on features of format and perspective that do not alter the content but affects interpretation nonetheless (Kahneman & Tversky, 2000). The phenomenon is widespread and spans from matters of economic behaviour up to scientific content itself, especially in settings where decision-making relevance is moderate or high. In a classic study, for instance, gain- versus loss-framed messages with identical substantial content ("The benefits of obtaining mammography" vs. "The risks of not obtaining mammography") were compared as concerns routine mammography in 40 year old women. Women who viewed the loss-framed message were predicted and found to be more likely to have undergone the test in a 12-month follow-up (Banks *et al.*, 1995). Similar or related effects have been observed in domains as diverse as meat consumption (Caso *et al.*, 2023), nanotechnology (Cobb, 2005), Covid-19 vaccination (Sasaki *et al.*, 2022), and sunscreen protection (Detweiler *et al.*, 1999).

Importantly, a predictable framing effect can also be deployed as a *nudge*, a tailored contextual arrangement which is meant to affect judgment and behaviour while leaving all the agent's options otherwise available (Thaler & Sunstein, 2021). But is nudging by framing a legitimate tool for science communication? The nudge approach has been criticized for its paternalistic aspect (e.g., Rebonato, 2012) and contrasted with a strategy of empowering people's understanding (e.g., Hertwig & Grüne-Yanoff, 2017). Given our analysis above, however, such contrast is largely a false alternative. Strengthening understanding in relevant scientific matters on the basis of the best available evidence from behavioural science is surely a much attractive goal in itself. However, the fulfilment of the conditions that are arguably required for such endeavour is by no means equally spread over the landscape of science communication settings. Consider the area close to vertex F in Figure 1. Here we have scientific content that is relevant for decision making conveyed to a large audience without the opportunity of repeated interaction. Under such conditions, it seems only reasonable to consider that information *has* to be framed in some way, and to calibrate it responsibly to favour beneficial outcomes, if possible at all. If we move away from vertex F towards E or H, on the other hand, framing may no longer be the most suitable strategy. When the size of the audience decreases and the frequency of interaction increases, it becomes possible to strengthen the scientific understanding of the audience. Targeted interventions can be conducted to assess audience understanding and overcome relevant difficulties. In those contexts, a greater attention to foster autonomy of judgment and choice is quite appropriate. Clinical consultation may be a case in point (Aggarwal *et al.*, 2014).

So nudging and empowering scientific understanding need not be competing strategies after all. Once the diversity of science communication is acknowledged and mapped, changing patterns of challenges and opportunities are bound to emerge in different areas, and different tools and approaches can simply complement each other.

The proposed framework, which acknowledges the diversity of science communication, also provides relevant insights for improving training. We can assess and reconsider how the diversity of science communication is addressed in science communication training. In current training, the existence of relevant divergences between communication scenarios receives insufficient attention (Baram-Tsabari & Lewenstein, 2017; Dudo *et al.*, 2021). Training usually focuses on generic communication skills (e.g., storytelling). Differences between scenarios are acknowledged, but they are restricted to the particularities of the audience. In this sense, it is explained that communicators should consider aspects such as the ideology, the history, and the social context of the audience. Nonetheless, particularities of the addressed scientific topic or the communicator-audience interaction are not considered.

In a recent study, Dudo *et al.* (2021) addressed the key characteristics of current science communication training programs based in North America. For that purpose, 32 semi-structured interviews with science communication trainers were conducted. The study found that training emphasises discrete skills such as storytelling, removing jargon, and creating visuals. Those skills are considered helpful across communication platforms (e.g., social media, face-to-face interviews, etc.). Nonetheless, strategic communication receives little attention. The only widely acknowledged strategic element is to "know the audience". In a similar study, Bennett *et al.* (2023) focused on science communication fellowship programs in North America. This qualitative study involved 25 semi-structured interviews with directors of science communication programs. Fellowship programs diverge from other training activities in important aspects. They usually involve context-specific practical skills (e.g., humanising scientists) and situated learning. Nevertheless, strategic communication also receives little attention in science communication fellowships.

The diversity of communication scenarios also encourages us to emphasise the different profiles of science communicators. Diverse scenarios, which involve different challenges, require diverse knowledge and skills. For example, consider medical consultation and public health campaigns. Skills related to addressing heterogeneous populations are not very relevant in the first case but crucial in the second. This means that there is no profile of science communicator that suits all types of scenarios. The appropriate profile depends on the particularities of the scenario. The diversity of profiles also has implications for science communication training. No programme can successfully train all profiles of science communicators at the same time (Baram-Tsabari & Lewenstein, 2017). The relevant knowledge and skills change across profiles. Training programs should, therefore, focus on certain profile of science communication.

In summary, based on the proposed framework, we can address potential strategies and developments in science communication. In this sense, nudging and strengthening understanding can be considered as complementary approaches that suit diverse kinds of scenarios. Moreover, we can assess science communication training and identify relevant limitations of current practice. In current training, the diversity of communication scenarios and profiles is usually overlooked. The proposed framework provides the basis for developing more diverse and specialised training programs.

7. Conclusions

Science communication is a broad field and involves very diverse activities, from popular science journalism to individual medical consultation. Nonetheless, the diversity of science communication usually receives insufficient attention by scientists, science communicators, and even science communication scholars. In this paper, we have introduced a framework for assessing the diverse scenarios, problems, and strategies of science communication. We have identified three crucial dimensions of science communication: size of the audience, frequency of interaction, and decision-making relevance of the topic. Those dimensions build up a three-dimensional space of science communication regarding which particular communication scenarios can be located. We have illustrated diverse areas of this space by particular cases of medical advising, public health communication, and podcast-based science communication about astronomy.

Based on the proposed framework, we have addressed relevant challenges of science communication. We argue that some areas of the space of science communication are usually associated with certain challenges. When the size audience is large, it is more likely to be heterogeneous and diverse in their epistemic attitudes. Moreover, obtaining reliable feedback becomes complicated. In scenarios where there is a high frequency of interaction, if messages remain similar over time, message fatigue can emerge. Furthermore, in certain contexts, it may be difficult to maintain consistency among messages. Finally, when addressed topics have high decision-making relevance, motivated science denialism and problems related with expertise may be encountered. We have also argued that, from the proposed framework, potential strategies and developments in science communication can be assessed. In this sense, nudging and strengthening understanding are shown to be not alternative approaches, but complementary strategies suitable for diverse kinds of scenarios. We have also argued that science communication training does not sufficiently take into account the diversity of scenarios and profiles of communicators.

We have focused on three important dimensions of science communication: size of the audience, frequency of interaction, and decision-making relevance. Considering those dimensions has positive aspects: it allows to account for diverse scenarios, the dimensions can often be assessed in advance, and it allows to anticipate certain difficulties and propose certain strategies. This can be useful for science communicators as well as for science communication scholars and educators. Nevertheless, the proposed framework may also benefit from further developments and refinements. In this sense, additional dimensions of science communication, which complement the ones considered here, could be integrated allowing for a richer input within the framework.

In particular, it should be noted that our framework does not explicitly consider the ethical aspects of science communication. Some of the aspects considered, however, may have important ethical implications and contribute to the ethical analysis of science communication. For example, decision-making relevance is often related with ethically laden communication. In the last decade, the ethical dimension of science communication has been extensively discussed (Desmond, 2024; John, 2019). Science communication is rarely neutral or value free: epistemic and non-epistemic values are usually involved in many stages of science communication. Values may guide decisions about frames, terminology, metaphors, and categories (Elliott, 2017). When deciding how to present a new scientific discovery, for example, science communicators are usually influenced by their own worldviews. In some cases, to favour their non-epistemic goals, communicators may even engage in wishful talking and endorse unestablished claims (John, 2019). Given the widespread presence of values, recommendations have been advanced to guide science communication practices. Many authors have argued for value transparency in science communication (e.g., Elliott, 2017; Intemann, 2024). According to those proposals, communicators should disclose the values involved in their decisions and messages. John (2019) instead holds that, to respect audience's autonomy, science communication should follow the Value-Apt Ideal. According to this ideal, communicated findings should not rely on non-epistemic values incompatible with those of the audience. Some authors, complementarily, have emphasised the role of the audience and argued that they have the ethical obligation to assign credibility judiciously (see, for instance, Holman, 2021). Other categorisations of science communication do consider (some aspects of) the ethical dimension of science communication (e.g., Desmond, 2024). We believe that these accounts should not be understood as alternative, but as complementary to the proposed three-dimensional framework. We encourage future work to explore the articulation and integration of diverse classifications.

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