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Is this good science communication? Construction and validation of a multi-dimensional quality assessment scale from the audience's perspective

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The expansion of science communication underscores the increasing importance of understanding what constitutes good science communication. This question concerns the public's understanding and engagement with science. The scholarly discussion has shifted from the traditional deficit model to a more dialog-oriented approach yet remains normatively anchored. There is a pivotal lack of attention to the audience's perspective regarding the question of what good science communication is. Moreover, different formats of science communication have hardly been researched thus far. Therefore, this paper introduces a multi-dimensional scale to capture the audience's assessment of specific science communication formats. We utilized a multi-step process to identify relevant criteria from both theoretical and practical perspectives. The instrument integrates 15 distinct quality dimensions, such as comprehensibility, credibility, fun, and applicability, structured according to different quality levels (functional, normative, user-, and communication-oriented). It considered theory-driven and practice-experienced categories and was validated through confirmatory factor analyses conducted on a German representative sample ($n = 990$). For validation, the scale was applied to a science blog post and a science video on homeopathy. After employing a seven-step process, we conclude that the newly devised scale effectively assesses the perceived quality of both blog and video science communication content. The overall assessment aligns with common target variables, such as interest and attitudes. The results regarding the different quality subdimensions provide a nuanced understanding of their contribution to the perceived overall quality. In this way, the scale aids in enhancing science communication in accordance with audience perceptions of quality. This marks the inaugural introduction of a comprehensive measurement instrument tailored to gauge quality from the audience's standpoint, rendering it applicable for utilization by both researchers and practitioners.

KEYWORDS

science communication, quality, audience perspective, evaluation, multidimensional

1 Introduction

Science communication is pivotal in rendering scientific knowledge understandable to the broader population, bearing significance at both the individual and societal levels (Gibbons, 1999; Kohring, 2012). Its pertinence is particularly pronounced in difficult situations such as the COVID-19 pandemic or in the context of climate change (Su et al., 2015; Newman et al., 2018; Scheufele et al., 2020; Loomba et al., 2021; Dempster et al., 2022), yet it remains equally germane in routine circumstances (Burns et al., 2003; Bromme and Goldman, 2014; Taddicken et al., 2020; Freiling et al., 2023). However, the communication of scientific knowledge is challenging as it opens up complex relationships, is very abstract, and is characterized by ambiguities and uncertainties (Popper, 2002)—which makes it challenging for laypeople who lack access to scientific sources, methodologies, and processes (Fischhoff and Scheufele, 2013). This raises the question of what is appropriate science communication for laypeople, how much scientific detail should be included, and how it should be presented, for example, how entertaining or hinting to everyday life it should be.

Science communication happens in various ways, from classic offerings such as discussion events and television documentaries to digital forms of communication such as online blogs and science videos to citizen science projects. It has been demonstrated that distinct formats of science communication elicit varying expectations from the audience (Wicke and Taddicken, 2020; Wicke, 2022). Against this background, considerations regarding the suitability of science communication come to the forefront, contingent upon the specific formats employed. Put differently, an inquiry emerges regarding the criteria defining good science communication content and whether and how these evaluative criteria diverge across various communication formats.

However, an examination of such quality issues is in its infancy in science communication. Standards or benchmarks for quality assurance have not been uniformly defined or established (Wormer, 2017). So far, they increasingly refer to concrete fields of application, such as the “Guidelines for Good Science PR” (Siggenger Kreis, 2016) or the evaluation of science journalistic reporting (Rögner and Wormer, 2017, 2020).

A vast body of literature examines communication training and its evaluation, with a common focus on enhancing oral and written proficiency, as well as mastering the comprehensive use of language (Besley and Tanner, 2011; Sharon and Baram-Tsabari, 2014; Besley et al., 2015, 2016; Dudo and Besley, 2016; Baram-Tsabari and Lewenstein, 2017; Rakedzon and Baram-Tsabari, 2017; Robertson Evia et al., 2018; David and Baram-Tsabari, 2020; Rodgers et al., 2020; Akin et al., 2021; Rubega et al., 2021; Besley and Dudo, 2022). While research in this area is invaluable, it mainly focuses on the communicators’ performances and often relies on mere self-assessments from trainees and is thus often flawed in substantive ways (Dunning et al., 2004). Research has just recently started to offer promising methods for integrating audience perspectives into evaluation processes (Rodgers et al., 2020; Rubega et al., 2021). However, as the impact on the target audiences is said to be the gold standard for science communication trainings (Rodgers et al., 2020), it is imperative to comprehensively incorporate the audience’s viewpoint.

Therefore, it is beneficial to consider not only research in science education but also approaches from communication studies.

Communication theories have long established that users play an active role not only in selecting content but also in directing their attention and processing specific elements (Chaiken, 1980; Ruggiero, 2000; LaRose and Eastin, 2004). Consequently, grasping the degree to which science communication aligns with audience expectations directly influences their utilization of such content, as well as their awareness and learning experiences (Hart and Nisbet, 2011; Hendriks et al., 2015; Romer and Jamieson, 2021). Prior research has shown that designing science communication in line with expectations can foster interest and thus increase the application of scientific knowledge (Serong et al., 2019; Wicke and Taddicken, 2021). Findings from journalism research also suggest links between audience perceptions of “good journalism” and their media use (Gil de Zúñiga and Hinsley, 2013; Loosen et al., 2020). On the contrary, dissatisfaction and frustration can even lead to a loss of trust (Donsbach, 2009; Fawzi and Obermaier, 2019; Arlt et al., 2020). Science communication should therefore meet the quality expectations of its audience (Wicke and Taddicken, 2020) to reach the population and provide them with access to science.

As usage metrics and high reach do not yet allow conclusions to be drawn about what the audience likes about the content (Hasebrink, 1997), audiences should be asked about it. This can increase the understanding of how science communication can be designed and derive ideas for modifying or optimizing formats.

However, until now, no comprehensive measure has been developed to assess audiences’ perspectives on the quality of specific science communication offers. While the goal of “effectiveness” in science communication is frequently emphasized, achieving a unified understanding of what constitutes effectiveness appears challenging (Bray et al., 2012; Bullock et al., 2019; Rubega et al., 2021). Clarity, credibility, and engagement of the public are key quality criteria underlying science communication (Rubega et al., 2021), yet they alone do not provide a comprehensive assessment, which should also encompass considerations of public relevance and societal meaningfulness.

Hence, within the scope of the current research, we have constructed and validated a “Quality Assessment Scale from the Audience’s Perspective” (QuASAP) guided by theory. This scale comprises 65 items on 15 dimensions. This standardized instrument allows both academics and practitioners to delve into the evaluations made by individuals. It is easily applicable to different science communication content. In the process of scale development, we deployed across two distinct science communication modalities, namely science blog posts and science videos, to gauge its applicability. As a dependable and robust tool, the scale enables scholars to compare individuals’ quality assessments across various dimensions and to investigate the predictive or explanatory potential of personal and situational attributes in this context.

2 Quality of science communication

The shift in perspective moves from assessing the effectiveness of science communication to adopting a normative approach, which emphasizes aims oriented toward society and democracy. The inquiry into the definition of ‘good’ science communication can be embedded in the normative frameworks of the science communication paradigms of *Public Understanding of Science* to the *Public Engagement with Science and Technology* (Mede and Schäfer, 2020). Concerning

public sphere theories, the inquiry into quality claims and criteria has a longstanding tradition in communication research. Here, it has been acknowledged that distinct quality dimensions and perspectives are relevant for journalistic content regarding the tension between democratic-theoretical and economic requirements (Arnold, 2009, 2023).

A debate about the quality of science communication has also recently unfolded, especially in light of the COVID-19 pandemic or the Fridays4Future movement (Wormer, 2017; Loomba et al., 2021; Dempster et al., 2022). This is accompanied, for example, by concerns about a possible loss of trust and credibility in science (Kohring, 2005; Weingart and Guenther, 2016; Cologna et al., 2024). However, even within this tradition of research, uniform definitions or standards for quality assurance have not been systematically delineated or established (Wormer, 2017; Wicke, 2022). One reason for this may be the challenge of formulating generally applicable, objective quality criteria, as these are, among other things, oriented to the respective format and audience as well as reference point and are thus dynamic and variable (Serong, 2015; Arnold, 2023). Likewise, judgments of quality depend to a large extent on the particular perspective and are, therefore, also subjective (Saxer, 1981; Hasebrink, 1997; Dahinden, 2004; Wicke, 2022). It is consequently crucial to acknowledge the viewpoint of the audience. Considering the audience's perspectives, ideas, and values leads to a positive quality assessment within the audience; and quality assessments significantly influence usage decisions (Katz et al., 1974; Ruggiero, 2000; Wolling, 2004, 2009; Mehlis, 2014).

Aligned with the constrained theoretical framework surrounding the definition of good science communication, empirical findings in this domain are also limited. In the intersection of journalism and science communication research, investigations have so far mainly focused on assessing environmental reporting as well as medical and health communication [e.g., Oxman et al. (1993), Schwitzer (2008), Wilson et al. (2009), Anhäuser and Wormer (2012), Bartsch et al. (2014), Rögener and Wormer (2017), and Serong et al. (2019)]. The quality criteria presented here are content-specific, primarily tailored to topics, and specifically relevant to print and online science journalism. Consequently, their application cannot be extended without limitations to the broad evaluation of diverse science communication content. There remains a conspicuous absence of a standardized framework for assessing the quality of science communication: "science communication [seems] to have initially pursued little effort to establish its own quality benchmarks in 15 years of PUSH [Public Understanding of Science and Humanities]" (Wormer, 2017; own translation). This deficiency encompasses both the absence of comprehensive theoretical development and the shortage of associated empirical measurement instruments that could be deployed to evaluate various forms of science communication.

Wormer suggests using established quality criteria from (science) journalism, which seems plausible to him "given the stated lack of established criteria for ensuring the journalistic quality of such products" (Wormer, 2017). Kohring (2012) argues that the relationship between science and the public has become increasingly problematic because of the impartation challenge. Consequently, science communication serves parallel functions to (science) journalism. These functions are information transfer, education and enlightenment, criticism and control, and acceptance (Kohring, 2012; Weitze and Heckl, 2016; Gantenberg, 2018). Therefore, Anhäuser and

Wormer (2012) contend that, rather than evaluating the quality of (science) journalism and science communication using distinct criteria, there is a need to develop cross-actor dimensions for quality assessment.

To date, assessments of science communication have predominantly been conducted through qualitative and hardly theory-driven research approaches (de Cheveigné and Véron, 1996; Cooper et al., 2001; Milde, 2009; Olausson, 2011; Maier et al., 2016; Milde and Barkela, 2016; Taddicken et al., 2020). For instance, research has shown that audiences place considerable emphasis on the comprehensibility of scientific content, which often tends to be abstract and complex, making it challenging to grasp. This entails the avoidance of technical terms and scientific jargon, as well as the contextualization of scientific findings (Bullock et al., 2019; Taddicken et al., 2020; Wicke and Taddicken, 2020, 2021). Furthermore, audiences seek information concerning the processes and methodologies employed in scientific research and awareness of uncertainties and discrepancies in scientific results (Maier et al., 2016; Milde, 2016; Milde and Barkela, 2016). In their perspective, good science communication also entails the presentation of a variety of (scientific) viewpoints and the multidisciplinary nature of research on a given topic, coupled with an emphasis on its relevance to everyday life, thereby enabling the "practical application" of scientific discoveries. In addition, content is perceived positively when it offers an element of entertainment and novelty (Wicke and Taddicken, 2021).

To provide a theoretical basement for the measurement of an audience's quality assessments, the integrative quality concept of Arnold (2009) is suitable. This quality concept has been called a "milestone" (Wyss, 2011) of journalistic quality research. Arnold (2009) positions the quality criteria within a tripartite theoretical framework, encompassing functional-system-oriented, normative-democracy-oriented, and audience-action-oriented dimensions. In this regard, the quality of journalism can be ascertained through two distinct avenues. Firstly, it can be derived from its fundamental functions, responsibilities, self-perceived role, and professional norms, effectively emanating "from within," so to speak. Secondly, quality assessment can be conducted by aligning journalism with societal values and media regulations while considering how journalism can actively engage with and cater to its audience.

In the context of science communication, there are additional specific tasks and functions that extend beyond the traditional roles of journalism (Wicke, 2022). Thereby, based on the quality dimensions of Arnold (2009) on journalistic media, Wicke (2022) introduces a dimension catalog that is extended by specific science communication-related criteria. This catalog differentiates between four different levels: First, the *functional-system-oriented level* captures the quality dimensions of *diversity*, *timeliness*, *relevance*, *credibility*, *independence*, *investigation*, *criticism*, and *accessibility/comprehensibility*. Second, the *normative-democratic level* includes *balance*, *neutrality*, and *respect for personality*. Third, a *user-action-oriented level* asks for *applicability* and *entertainability*. Fourth and last, the *science communication/format-specific level* considers *education*, *enlightenment and information*, *legitimacy and acceptance*, *dialog and participation*, *emotions*, and *context/situation* (Wicke, 2022; own translation). In her study, this catalog is objective of the investigation of congruencies between audiences' and science communicators' perceptions of specific functions of science communication. Furthermore, she captures quality expectations from the audience toward an expert debate.

According to the results, credibility, accessibility, independence, neutrality, and plurality are the most important expectations toward the science communication format expert debate. However, although these expectations were nearly completely fulfilled, the overall assessment of the expert debate was only on a medium level (Wicke, 2022). In this regard, it remains unclear whether the survey adequately addressed all quality dimensions that are pertinent to the intended audience. In addition, Wicke (2022) advocates for developing a standardized survey tool that can be easily used and facilitates cross-format, cross-topic, and cross-temporal comparisons.

In pursuit of this objective, we will integrate this compendium of quality criteria into a fundamental scale construction process, encompassing theoretical foundations and expert assessments derived from academic research and practical domains.

3 Scale development

The development of new scales must undergo multiple iterations to ensure their validity. In this context, validity refers to the degree to which the instrument accurately measures its intended criteria. Therefore, rigorous testing and refinement were essential to ensure the scale had clear and precise wording, well-defined parameters and encompassed the critical aspects required to evaluate science communication. In order to assess the quality of science communication from an audience's perspective, we developed a new questionnaire through a foundational seven-step process. We will describe this process in the following.

3.1 Process

The multi-step process is composed of a total of seven steps in three different development phases (Table 1):

In the first phase of *identification of relevant dimensions and itempool*, we started with a collaborative *brainstorming* session with our research project's practical collaborators. The panel of expert practitioners involved in this group discussion comprised

professionals from various domains, including university communication, research institution communication, individual science communication by scientists, a science museum, and a science center dedicated to bridging the gap between scientific knowledge and the public. The step aimed to capture the whole range of quality aspects, considering the practitioners' experiences, ideas, and aims.

Further, to incorporate the current state of research, we conducted an extensive literature review (step 2: *theory*). This review was the foundation for deriving quality dimensions and items, drawing insights from academic publications, policy documents, and available practical guidelines. As introduced above, the categories of Arnold (2009) and Wicke (2022) were important sources.

As a result, we developed an extensive pool of various items. Our aim was to create at least two different items for each aspect to achieve a pool at least two times larger than needed (Schinka and Velicer, 2003; Kline, 2013).

In the second phase of *refinement and pretesting*, we started with *reflection on dimensions* (third step) in expert interviews conducted with six practitioners, three from our collaboration partners and three from other positions. The objective was to enhance the content validity of dimensions and items by incorporating practical insights and experiences from these experts.

In the fourth step, we focused on *methodological improvement* by crafting specific items aligned with the identified dimensions. To enhance the robustness of our questionnaire, we convened a workshop involving six experienced survey and science communication researchers. To test for content validity by evaluating expert judges (Boateng et al., 2018). During this workshop, the experts were asked for their feedback concerning the conceptualization of the construct, their assessment of the chosen underlying dimensions, and their appraisals of each specific item, alongside the assessment of the entire instrument. During this stage, participants were encouraged to articulate any feedback, such as suggestions for item enhancement, potential exclusions, or modifications aimed at enhancing item clarity. We ensured that each item underwent rigorous scrutiny with particular attention to wording, such as ensuring clarity, comprehensibility, and balance, and to the logical sequence within the questionnaire.

TABLE 1 Applied multi-step approach to identify relevant criteria from science and practice to develop a multi-dimensional quality assessment scale from the audience's perspective.

Step	Aim	Procedure	Perspectives
I Identification of relevant dimensions and itempool			
1. Brainstorming	Capture the whole range of quality aspects	Expert group discussion	Science and practice
2. Theory	Derive dimensions and categories	Literature review	Scientific publications, policy papers, guidelines from practice
II Refinement and pretesting			
3. Reflection on dimensions	Expand the dimensions by means of practical experience to increase content validity	Expert interviews	Practitioners
4. Methodological improvement	Optimize dimensions and items from a methodological perspective (expert validity)	Workshop	Scientists
5. Cognitive pretest	Ensure face validity and item comprehensibility	Test and interview	Students
6. Pretest	Test application of instrument on two different stimuli	Online survey	Audience (convenient sample)
III Validation			
7. Validation	Application of instrument and replication	Online survey	Audience (representative sample)

In the fifth step, we invited five advanced communication students to complete the resultant questionnaire and engage in discussions about the comprehensibility of the items. This *cognitive pretest* aimed to confirm the face validity of the questionnaire. These interviews served the following purposes: (1) to ascertain if participants comprehended the items, (2) to gauge if participants perceived the items in the same manner as intended by the researchers, and (3) to explore how participants calibrated the item along with its response options.

In the sixth step, following the final modifications, the scale underwent an empirical *pretest*. We conducted an online survey with a convenient sample of $n = 69$ participants. Here, we were interested in how appropriate our two different stimuli (blog post, video) were for application in an online survey. Moreover, despite the relatively small sample size, we conducted an exploratory factor analysis to assess how the items interacted. We utilized the results only to identify potentially problematic items with low standard deviations or high kurtosis values. Subsequently, we revisited and refined the identified items through another round of methodological improvements.

In the final step of *validation*, step seven of our multi-step scale testing process, we administered another online survey using the refined scale for an initial test and its replication. For this phase, we employed Qualtrics to ensure we obtained a sample representative in terms of sex, age, and education. Due to the significance of this concluding step, it will be introduced in the next chapter alongside the presentation of the final scale.

3.2 Instrument: quality assessment scale from the audience's perspective (QuASAP)

To present the instrument called the Quality Assessment Scale from the Audience's Perspective—QuASAP—we will follow the suggested systematization of Wicke (2022), adapted from Arnold (2009).

3.2.1 The functional-system-oriented level

On the functional-system-oriented level, our scale development process confirmed the dimensions introduced by Arnold (2009) and Wicke (2022) but reflects the peculiarities of science communication (Table 2).

For *diversity*, it was identified that the presentation of distinct scientific perspectives from different disciplines and research fields is important. *Topicality* is to include the latest research findings. *Relevance* is meant as societal relevance. Individual relevance is also considered important, but is called applicability and one of the following dimensions. *Credibility* was identified as a major quality dimension for science communication. This is in line with prior research [e.g., Bucchi (2017), Vraga et al. (2018), and Wicke (2022)]. As Hendriks et al. (2015) introduced a well-adopted scale for laypeople's trust in experts (METI), we relied on this.

The classic quality dimensions of *neutrality* and *correctness* were confirmed as relevant dimensions, although correctness is seen more as a result of research than (journalistic) investigation. Further, a critical perspective on science, including the contextualization of findings (*critique*), was highlighted as relevant.

Comprehensibility of science communication is one of the most discussed quality aspects. The focus is often on using technical terms and scientific jargon, and the recommendation is to reduce it (Dean, 2012; Scharrer et al., 2012; Sharon and Baram-Tsabari, 2014; Bullock et al., 2019; Willoughby et al., 2020; Meredith, 2021). However, the overall comprehensibility of the content, together with the comprehensibility of structures and illustration through examples related to the layperson's world, was also mentioned as important [see also Taddicken et al. (2020) and Siggenger Kreis (2016)].

3.2.2 The normative-democracy-oriented level

Two dimensions of our instrument refer to the normative-democracy-oriented level of Arnold (2009). The idea of *objectivity* through a separation of news and opinion was adopted. The aspect of balanced reporting as mentioned by Arnold (2009), converged with plurality and is thus represented. *Respect for personality* was acknowledged as important when asked for but was not actively mentioned by the practitioners (Table 3).

3.2.3 The user-action-oriented level

Originally introduced were *applicability* and *entertainingness* (Arnold, 2009) and are confirmed here. For applicability, the relevance for people's everyday life and, thus, the level of usefulness for their daily life was mentioned as an important quality aspect (Table 4).

3.2.4 The science communication specific level

In addition to the original integrative quality concept of Arnold (2009) and Wicke (2022) added five further dimensions to consider science communication or format-specific aspects. These include education, enlightenment, and information, as well as legitimation and acceptance of science as central tasks of science communication: The population should be informed and educated, and their understanding of and for science should be promoted. Since science depends, among other things, on societal resources and the trust of the population, it must also secure its public legitimacy (Weingart, 2011). An increasing orientation toward the public engagement paradigm in outreach has increased the importance of interactions between science and the public and produced numerous formats, making dialog and participation another dimension (van der Sanden and Meijman, 2008; Bubela et al., 2009). Furthermore, emotions were included, as science and environmental topics are not only communicated in an objective and factual way, but in many cases emotionalization can be observed (Huber and Aichberger, 2020; Lidskog et al., 2020; Taddicken and Reif, 2020). Last, Wicke (2022) added situational contexts to consider pragmatic and organizational aspects, similar to criteria developed to capture the aesthetic design of a media product (Göpfert, 1993; Dahinden, 2004).

The multi-step process was applied—initially relying on the ideas of Arnold and Wicke as described above—with only three dimensions being identified in the process (Arnold, 2009; Wicke, 2022) (Table 5): First, the *presentation* of the content, which considers aspects of education, enlightenment, and information. Here, aspects of multimodality were integrated. Aspects of *dialog* and participation were also identified as relevant quality aspects (according to the paradigm of *Public Engagement with Science*); thus, it is asked for perceived

TABLE 2 Items for dimensions diversity, topicality, relevance, credibility, neutrality, correctness, critique and comprehensibility (functional-system-oriented level).

Diversity¹
The video / The blog post ² highlights the different perspectives on the topic.
The video / The blog post ² highlights the topic from different (scientific) perspectives.
The video / The blog post ² presents different positions and opinions in a balanced way.
Topicality¹
The video / The blog post ² presents recent scientific findings.
The video / The blog post ² addresses recent events and developments related to the topic.
The video / The blog post ² deals with a topical issue.
Relevance (of the topic)¹
In the video / blog post ² shows why science is concerned with homeopathy ² .
The video / The blog post ² shows why homeopathy ² is important for society.
The video / The blog post ² deals with a topic that can also affect me personally.
Credibility³
competent – incompetent
intelligent – unintelligent
well educated – poorly educated
professional – unprofessional
experienced – inexperienced
qualified – unqualified
sincere – insincere
honest – dishonest
just – unjust
fair – unfair
moral – immoral
ethical – unethical
responsible – irresponsible
considerate – inconsiderate
Neutrality¹
I have the impression that I am informed independently.
I have the impression that the content is conveyed neutrally.
I have the impression that possible conflicts of interest or financial dependencies are mentioned.
I have the impression that the information bases are made transparent.
Correctness¹
I have the impression that the content of the video / blog post ² is researched correctly.
I have the impression that the content of the video / blog post ² has been carefully prepared.
I have the impression that the content of the video / blog post ² is presented in a factually correct way.
Critique¹
The video / The blog post ² , the content is critically examined.
In the video / the blog post ² , the content is contextualized.
Comprehensibility¹
In the video / the blog post ² , scientific content is explained in an understandable way.
Illustrative examples are used.
The content is conveyed in comprehensible language, e.g., technical terms are explained appropriately.
I was able to understand connections very well.
I was able to follow the content very well.
I felt very well taken care of.

¹Answers on a 5-point rating scale from '1' – strongly disagree, to '5' – strongly agree.

²Replace if necessary.

³Items from Hendriks et al. (2015), answers on a 5-point rating scale applying the word (semantic-differential pairs).

TABLE 3 Items for dimensions objectivity and respect (normative-democracy-oriented level).

Objectivity ¹
The content is conveyed objectively.
The content is reported in a factual way.
In the video / blog post ² it is apparent whether it is fact or opinion.
In the video / blog post ² it is distinguished between facts and opinions.
Respect (for personality) ¹
In the video / blog post ² the behavior is respectful.
In the video / blog post ² the conversational tone is appreciative.
In the video / blog post ² the atmosphere is pleasant.
In the video / blog post ² viewers / readers are treated appreciatively.

¹Answers on a 5-point rating scale from '1' – strongly disagree, to '5' – strongly agree.

²Replace if necessary.

TABLE 4 Items for dimensions applicability and entertainingness (user-action-oriented level).

Applicability ¹
The content conveyed shows possible answers to everyday questions.
The content conveyed shows that scientific knowledge can be important in everyday life.
The content conveyed can be applied by me in my everyday life.
The content conveyed helps me a lot in making personal decisions.
Entertainingness ¹
The video / blog post ² is very interesting.
The video / blog post ² entertains me very well.
The video / blog post ² conveys content in an entertaining way.

¹Answers on a 5-point rating scale from '1' – strongly disagree, to '5' – strongly agree.

²Replace if necessary.

possibilities to comment, of interactivity and dialog. Last, *enjoyment* was identified as an important emotion and was captured here.

4 Validation

4.1 Method

4.1.1 Sample and sampling procedures

We commissioned the survey company Qualtrics to collect a sample of participants that represented the adult German population regarding age, education, and sex (see quota in Table 6). Field time started 10/22/2021 and ended 11/09/2021. Of the initial 1,075 participants, the first 77 respondents had to be excluded for technical issues regarding the survey implementation, five because all or all but one of the relevant variables were missing, and three because the participants took more than 15 h to complete the online survey. Of the remaining 990 participants, 472 were randomly selected to see the blog post and 518 to watch the video. We partitioned the sample and subjected it to varied stimuli to facilitate the administration of the scale on two occasions. The participants' key characteristics are shown in Table 6. The data were collected in October and November 2021, and participation took on average 17.3 min ($SD=15.63$, $min=7.00$, $max=275.27$; Blog: $M=18.10$ min, $SD=19.19$, $min=7.00$, $max=275.27$; Video: $M=16.57$ min, $SD=11.41$, $min=7.00$, $max=126.18$).

TABLE 5 Items for dimensions presentation, dialog, and enjoyment (science communication specific level).

Presentation ¹
The content is conveyed in a very appealing way.
The content is conveyed in a way that is appropriate for the video / blog post ² .
The content is conveyed in a way that is appropriate for homeopathy ² .
The visualizations of the information (e.g., graphics, images) are appealing.
I like the multimedia preparation of the information.
Dialog ¹
In the video / blog post ² or in the comments viewers / readers are able to express their questions and opinions.
In the video / blog post ² or in the comments viewers / readers are involved.
In the video / blog post ² or in the comments viewers / readers are addressed.
In the video / blog post ² or in the comments it seems that the two YouTubers / the experts are open to an exchange with the viewers / readers.
The video / blog post ² is dialog oriented.
Enjoyment ¹
The content conveyed is inspiring.
I had a lot of fun watching / reading the content.
I enjoyed getting involved with science and homeopathy ² .
Watching the video / reading the blog post ² was an experience for me.

¹Answers on a 5-point rating scale from '1' – strongly disagree, to '5' – strongly agree.

²Replace if necessary.

4.1.2 Procedure and materials

First, participants were informed about their privacy rights and that data were analyzed anonymously via written statement, asked about their written consent to participate in the survey and to provide personal data. Basic demographics as well as reception prerequisites (e.g., prior knowledge and attitudes) were assessed. Second, they were randomly assigned to a blog or video condition.

Subsequently, they either read a blog post or watched a video. Both were authentic materials and dealt with the critical view of science on homeopathy. We selected homeopathy as our focus because it represents a typical topic within alternative medicine that is familiar to many and closely tied to everyday life. Despite its widespread recognition, there is limited or no evidence supporting its effectiveness. The blog post was published on "scienceblogs.de," a private German popular science platform, and was written by a health scientist [<https://scienceblogs.de/gesundheits-check/2014/03/22/10-gruende-an-die-homoeopathie-zu-glauben-oder-es-sein-zu-lassen/>] (own translation: 10 reasons to believe in homeopathy or to drop it). The video was created by a popular German video channel on YouTube, with a duration of approximately 3 min and more than 40,000 views [<https://www.youtube.com/watch?v=FkEMbhH2gms>] (own translation: Homeopathy – The most expensive placebos in the world?). Both stimuli are in response to the lack of evidence and are detailed in the Supplementary Appendix S1.

After this stimulus, participants were asked to state whether they interacted with the stimulus as instructed. Individuals who did not watch the whole video or read the whole article were directly excluded from further participation. Third, the participants were asked to rate the quality of the blog article or video on the introduced quality dimensions. Fourth, they were asked about their subjective impression of the stimulus' impact on them.

TABLE 6 Overview of basic demographic variables in the sample separated by group (blog vs. video) and desired quota.

	Blog (n = 472)	Video (n = 518)	Total (n = 990)	Desired quota
Age				
18–24 years	47 (10%)	54 (10%)	101 (10%)	10.20%
25–34 years	79 (17%)	95 (18%)	174 (18%)	17.35%
35–44 years	90 (19%)	92 (18%)	182 (18%)	17.28%
45–54 years	93 (20%)	115 (22%)	208 (21%)	20.54%
> 54 years	161 (34%)	162 (31%)	323 (33%)	34.65%
NA	2 (0%)	0 (0%)	2 (0%)	
Mean (SD)	45.96 (15.33)	45.01 (15.14)	45.46 (15.23)	
Range	18–79	18–88	18–88	
Education				
ISCED 0–2	82 (17%)	89 (17%)	171 (17%)	15.97%
ISCED 3–4	241 (51%)	288 (56%)	529 (53%)	57.01%
ISCED 5–8	148 (31%)	140 (27%)	288 (29%)	26.79%
NA	1 (0%)	1 (0%)	2 (0%)	
Sex				
Male	238 (50%)	257 (50%)	495 (50%)	50.15%
Female	233 (49%)	255 (49%)	488 (49%)	49.52%
Diverse	1 (0%)	2 (0%)	3 (0%)	
NA	0 (0%)	4 (1%)	4 (0%)	

4.1.3 Measures

4.1.3.1 Quality assessment scale from the audience's perspective

In order to assess the quality of science communication from an audience's perspective, we applied (see 3.2).

4.1.3.2 Overall quality ratings

While the overarching quality factor of our scale indicates the general quality judged by the audience, the subdimensions and items offer insights into how this quality perception is formed. The strength of this scale lies in its ability to provide a nuanced understanding of the various quality subdimensions.

To assess the extent to which the overarching quality factor correlates with single-item quality ratings (criterion validity), we included two items: The first item directly asked participants how well they liked the blog post (the video) in general [original: "Wie gut hat Ihnen der Blogbeitrag (das Video) insgesamt gefallen?"] and the second asked whether participants would recommend the items to others [original: "Würden Sie den Blogbeitrag (das Video) weiterempfehlen?"].

As the participants were not asked any sensitive questions, e.g., regarding political, religious or sexual attitudes, a statement from the ethics committee was not obtained.

4.2 Findings

All data analyses were completed using R (R Core Team, 2022) and R Studio (Posit Team, 2022). The confirmatory factor analysis (cfa) was calculated using the lavaan package (Rossee, 2012). A

detailed description of all packages used is provided in [Supplementary Table S2](#). In order to increase comparability between the original study and its replication, both are presented in each paragraph. However, the replication analysis was completed after the original analysis.

4.2.1 Analysis of quality items

4.2.1.1 Blog data

All items were left skewed (*range*: -1.13 to -0.19), with means ranging from 3.20 ($SD=1.12$) to 4.10 ($SD=0.89$), revealing no evidence of a severe ceiling effect. The number of non-responses per item went from two to 30. Missing values were excluded from the analysis of the respective item.

4.2.1.2 Video data

Similar results were obtained, replicating the analysis with video data. All items were left skewed (*range*: -1.19 to -0.27), and the means ranged from 3.16 ($SD=1.26$) to 4.04 ($SD=1.08$). Up to 25 missing values on the item level were removed from the analysis.

A detailed analysis of the characteristics of all items is provided in [Supplementary Table S3](#).

4.2.2 Scale analysis

4.2.2.1 Blog data

Internal consistency: Cronbach's alpha of the subscales ranged from 0.76 to 0.95, showing medium to high internal consistency. One exception was the critique subscale, which showed a lower internal consistency ($\alpha=0.64$). The lower value is unsurprising as this subscale consists of only two items.

Factorial validity: The factorial validity was tested using a cfa ($n=472$, $df=2,130$). The model was estimated using the maximum likelihood estimation with robust standard errors (Huber-White method) and scaled test statistics. Missing data were assumed to be missing at random (MAR) and were estimated on the sample level using complete information maximum likelihood estimation. Although the expected model differed significantly from the observed model [$Chi^2(2130)=3640.49$, $p<0.001$], if relativized at the degrees of freedom, then a close fit to the data is reached ($rRMSEA=0.046$, 90% CI [0.043, 0.048]; [MacCallum et al., 1996](#)). The user model outperformed the baseline model (*robust CFI*=0.91, *robust TLI*=0.90) and accurately fit the data. All standardized factor loadings (betas) of the subdimensions differed significantly from 0 ($p<0.001$) and ranged from 0.51 to 0.86, indicating a bad to good fit. All standardized loadings of the superordinated quality factor on the subdimensions reached significance ($p<0.001$) and ranged from 0.69 to 0.92, showing an acceptable to good fit. An overview of all standardized factor loadings is provided in [Figure 1](#).

Criterion validity: To control for criterion validity, participants were asked how well they liked the blog entry ($n=459$, $M=3.65$, $SD=1.06$) and whether they would recommend it to others ($n=457$, $M=3.47$, $SD=1.18$). Both criterion variables were intercorrelated ($n=450$, $r=0.76$, $p<0.001$). The conducted latent quality variable was significantly correlated to both the direct overall evaluation ($n=459$, $r=0.63$, $p<0.001$) and the recommendation ($n=457$, $r=0.65$, $p<0.001$). From this, we conclude a high criterion validity.

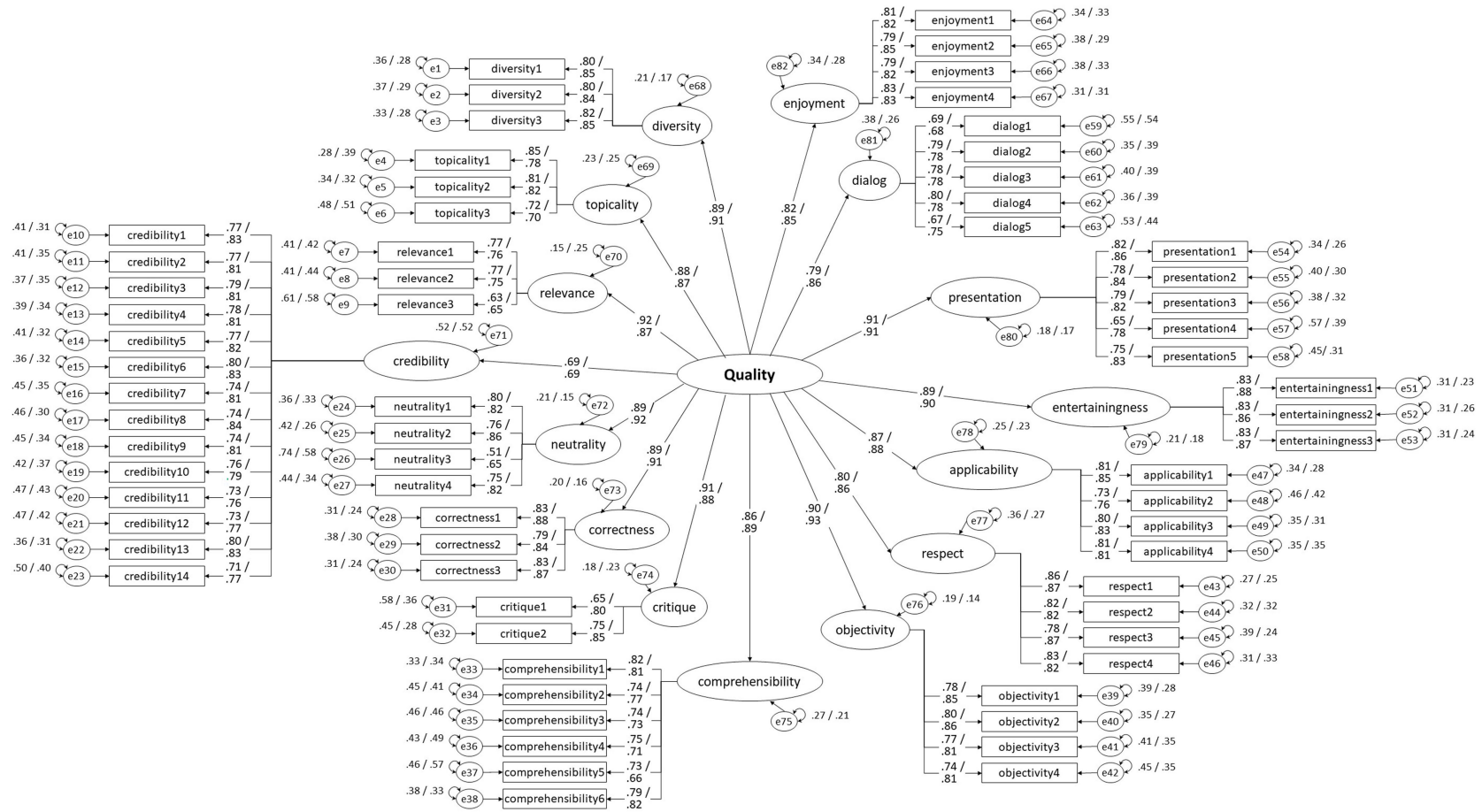


FIGURE 1

Measurement model consisting of one first-order quality factor, 15 second-order quality factors, and 65 quality indicators. The numbers represent the standardized loadings and variances separated by group (blog group/ video group). Blog: cfa ($n = 472$, $df = 2,130$): $\chi^2(2130) = 3640.49$, $p < 0.001$, $rRMSEA = 0.046$, 90% CI [0.043, 0.048]; $rCFI = 0.91$, $rTLI = 0.90$; Video: cfa ($n = 518$, $df = 2,130$): $\chi^2(2130) = 3708.75$, $p < 0.001$, $rRMSEA = 0.045$, 95% CI [0.042, 0.047]; $rCFI = 0.93$, $rTLI = 0.92$.

TABLE 7 Factor loadings of quality dimensions on the overall quality assessment of the audience (blog / video).

Variable	$\beta_{\text{blog}} / \beta_{\text{video}}$	$b_{\text{blog}} / b_{\text{video}}$	$SE_{\text{blog}} / SE_{\text{video}}$
Diversity	0.89*** / 0.91***	0.93 / 1.00	0.07 / 0.06
Topicality	0.88*** / 0.87***	0.99 / 0.84	0.06 / 0.06
Relevance	0.92*** / 0.87***	0.93 / 0.85	0.07 / 0.06
Credibility	0.69*** / 0.69***	0.69 / 0.74	0.06 / 0.06
Neutrality	0.89*** / 0.92***	0.95 / 1.05	0.07 / 0.06
Correctness	0.89*** / 0.91***	0.97 / 1.01	0.07 / 0.06
Critique	0.91*** / 0.88***	0.80 / 0.89	0.06 / 0.05
Comprehensibility	0.86*** / 0.89***	0.96 / 0.89	0.06 / 0.06
Objectivity	0.90*** / 0.93***	0.91 / 1.01	0.08 / 0.06
Respect	0.80*** / 0.86***	0.80 / 0.93	0.07 / 0.06
Applicability	0.87*** / 0.88***	1.02 / 1.07	0.06 / 0.05
Entertainingness	0.89*** / 0.90***	1.04 / 1.09	0.06 / 0.05
Presentation	0.91*** / 0.91***	0.99 / 1.12	0.05 / 0.05
Dialog	0.79*** / 0.86***	0.72 / 0.87	0.07 / 0.06
Enjoyment	0.82*** / 0.85***	1.00 ^a / 1.00 ^a	- / -

$n_{\text{blog}} = 472$, $n_{\text{video}} = 518$, β = standardized factor loadings, b = unstandardized factor loadings, SE = standard error. *Enjoyment was used as a reference variable, so, its loading was set to 1. *** $p < 0.001$.

4.2.2.2 Video data

Internal consistency: Replicating the scale analysis with the video data again showed similar results. Cronbach's alpha reached 0.76 to 0.96, showing medium to high internal consistency.

Factorial validity: Again, a cfa ($n = 518$, $df = 2,130$) with the same specification and estimation methods as the original study was conducted and revealed similar results. Relativized to the degrees of freedom, the expected model showed a close fit to the observed model [$\chi^2(2130) = 3708.75$, $p < 0.001$, $r_{\text{RMSEA}} = 0.045$, 90% CI (0.042, 0.047)] and outperformed the baseline model ($r_{\text{CFI}} = 0.93$, $r_{\text{TLLI}} = 0.92$). All standardized loadings reached significance ($p < 0.001$). Loadings from subdimensions on items ranged from 0.65 to 0.88, and loadings from the superordinate factor to the subdimensions ranged from 0.69 to 0.93, indicating an acceptable to good fit. Figure 1 provides an overview of all the loadings.

Criterion validity: Both criterion variables, the overall evaluation ($n = 511$, $M = 3.63$, $SD = 1.22$) and the recommendation to others ($n = 513$, $M = 3.42$, $SD = 1.34$) were intercorrelated ($n = 509$, $r = 0.83$, $p < 0.001$). Again, the latent quality factor was significantly correlated to the direct overall evaluation ($n = 511$, $r = 0.72$, $p < 0.001$) and the recommendation ($n = 513$, $r = 0.69$, $p < 0.001$), which indicates good validity.

The correlation analysis of the dimensions can be found in Supplementary Table S4, an overview of the factor loadings of each item in Supplementary Table S5.

Table 7 contains information on the extent to which the 15 quality dimensions relate to the audience's overall quality assessment. All 15 dimensions make a very high explanatory contribution to the overall concept of quality. With the exception of the dimension of credibility, all values are even in an exceptionally high range.

This finding, that all 15 dimensions explain the overarching quality factor to a high degree should be emphasized, as it shows that all dimensions were indeed highly relevant for the overall quality perception. This had been theoretically assumed in advance, but would not necessarily have been confirmed by the empirical data.

The results (Figure 1) indicate that several subdimensions, notably objectivity, presentation, neutrality, correctness, diversity, relevance, critique, and entertainingness, displayed high path coefficients in relation to the overall quality. Additionally, applicability, topicality, and comprehensibility were highly important. Although with slightly lower values, the subdimensions of respect, dialog, and enjoyment also made significant contributions to the overall assessment. Credibility exhibited the lowest values, albeit still at a moderate level. One possible explanation for this discrepancy could be attributed to the differing item format of the original METI scale utilized in this study.

Overall, it becomes apparent that the subdimensions of societal meaningfulness were not less important than subdimensions more oriented to the individual user.

Therefore, for a comprehensive quality assessment oriented toward the audience's expectations, these 15 dimensions should be conducted. However, the QuASAP scale also allows for a selection of quality dimensions.

The extent to which various quality dimensions correlate with typical target variables of science communication is also of interest to assess the appropriateness of the QuASAP instrument. Here, we chose to examine six different concepts: interest, knowledge, attitudes, behavior, abilities (to understand and engage), and self-efficacy—each pertaining to both science in general and the specific topic of homeopathy. The number of items assessed varied between 4 and 8 (refer to Supplementary Table S6 for additional details and specific items), and Cronbach's alpha for each variable demonstrated satisfactory reliability (Table 8).

The correlation analyses revealed that all correlations are of medium to high magnitude and statistically significant at a $p \leq 0.001$ level (Table 8). This demonstrates a moderate to strong relationship between the science communication presented to the participants and their interest in and perceptions of the science topic. Therefore, it suggests that the QuASAP scale effectively captured associations between its measures and external target variables.

As mentioned, the primary advantage of the scale is its ability to elucidate the various subdimensions and their connections to various external concepts. Notably, upon examining the correlation values, credibility consistently exhibits the lowest correlation. It is reasonable to posit that credibility serves as a fundamental prerequisite, becoming more salient when perceived as lacking—specifically when the presented content is not deemed credible.

The quality dimensions with the highest correlations with the chosen target concepts vary. This leads to a nuanced depiction, highlighting the strengths of a quality scale with different subdimensions. Different science communication offerings may pursue different goals; thus, the detailed exploration of individual dimensions can reveal the extent of relationships present.

When examining the individual target variables, interest and behavior demonstrate the strongest correlation with enjoyment. This means that a higher level of enjoyment is associated with a higher level of interest in the topic and corresponding research as well as increased behavior, which was queried here in relation to information searches and participation in discussions.

TABLE 8 Correlation analyses of quality dimensions and typical target concepts of science communication.

	Interest ($\alpha = 0.897$)	Knowledge ($\alpha = 0.932$)	Attitudes ($\alpha = 0.888$)	Behavior ($\alpha = 0.927$)	Abilities ($\alpha = 0.888$)	Self-efficacy ($\alpha = 0.887$)
Diversity	0.601***	0.758***	0.662***	0.580***	0.678***	0.595***
Topicality	0.631***	0.699***	0.624***	0.573***	0.654***	0.569***
Relevance	0.656***	0.703***	0.669***	0.615***	0.640***	0.631***
Credibility	0.460***	0.568***	0.485***	0.399***	0.521***	0.416***
Neutrality	0.606***	0.742***	0.670***	0.587***	0.683***	0.603***
Correctness	0.618***	0.769***	0.663***	0.548***	0.676***	0.541***
Critique	0.595***	0.679***	0.610***	0.566***	0.640***	0.557***
Comprehensibility	0.587***	0.635***	0.576***	0.533***	0.606***	0.525***
Respect	0.628***	0.630***	0.665***	0.558***	0.600***	0.596***
Applicability	0.545***	0.752***	<u>0.700***</u>	0.695***	<u>0.730***</u>	0.516***
Entertainingness	0.677***	0.697***	0.653***	0.648***	0.681***	<u>0.706***</u>
Presentation	0.656***	0.715***	0.670***	0.614***	0.677***	0.627***
Dialog	0.587***	0.666***	0.621***	0.587***	0.630***	0.572***
Enjoyment	<u>0.702***</u>	0.686***	0.662***	<u>0.718***</u>	0.684***	0.692***

*** $p < 0.001$. Highest values in each column underlined.

Attitudes and abilities display the highest correlation with the quality dimension of applicability. This implies that individuals who perceived higher applicability in science communication content exhibited greater capacity to form opinions, as well as to comprehend, and engage with the content. This assertion is plausible because perceiving science as applicable to one's own life should reduce the threshold for contemplating and engaging with science issues.

The greatest correlation for knowledge is observed with correctness, reflecting the assessment of how truthful the presented information is in relation to the perception of how much one has learned about science and the topic of homeopathy. This correlation is also logical.

In addition, science communication can aim to enhance self-efficacy, defined as an individual's belief in their capacity to execute behaviors necessary for specific performance attainments (Bandura, 1977). Interestingly, entertainingness exhibits the highest correlation in this context, suggesting that an entertaining way of presenting science may benefit the intentions to engage with science information, such as reading academic content.

However, it is important to note that these correlation analyses primarily provide insights into the suitability of different quality dimensions in explaining selected goals of science communication. This study was not intended to investigate the specific effects of the science communication content on the participants, but rather to indicate whether the QuASAP scale can accurately identify relationships between the scale's measures and external variables.

5 Conclusion

This paper aimed to introduce a quality assessment scale for science communication that acknowledges the audience's perspective. Although a valuable strand of research exists to assess the effectiveness of science communication and science communication trainings (Besley and Dudo, 2022) with integrating the audience perspective on the science communicators' outcomes, and alongside the ongoing normatively anchored discussion on the societal and democratic

quality of science communication (Fähnrich, 2017; Mede and Schäfer, 2020), it is striking how far the audience perspective is neglected in the second strand of research. However, as the impact on the target audiences is considered the gold standard for science communication trainings (Rodgers et al., 2020), and as it has been found that the audience perspective on journalism is related to its usage and information processing (Gil de Zúñiga and Hinsley, 2013; Loosen et al., 2020), there is an urgent need for a comprehensive assessment that not only captures aspects of clarity and credibility but also considers public relevance and societal meaningfulness. To introduce such a comprehensive assessment was the aim of this study.

The question of what good science communication is should not only be answered from an academic standing, even if it is based on the idea of considering the public perspective. The practitioners' viewpoints should also be acknowledged, as extensive discussions on this question and manifold experiences have been developed (e.g., the "Guidelines for Good Science PR" (Siggenger Kreis, 2016)). The variety of science communication offerings has massively increased over the last few decades (Bubela et al., 2009; Bucchi and Trench, 2014). This underscores the importance of measurement instruments based on cross-actor dimensions instead of using distinct criteria to conduct a single format's success.

This study follows the suggestion of Wormer (2017) when adopting established quality criteria from (science) journalism and builds upon prior work of journalism and science communication researchers (Arnold, 2009; Wicke, 2022). A multi-step process of seven different stages was carried out, and prior academic research and practitioners' experiences were integrated to validate a multi-dimensional scale of quality assessments of science communication from the audience's perspective—the QuASAP.

The instrument integrates 15 distinct quality dimensions: *Diversity*, *Topicality*, *Relevance*, *Credibility*, *Neutrality*, *Correctness*, *Critique*, *Comprehensibility*, *Objectivity*, *Respect*, *Applicability*, *Entertainingness*, *Presentation*, *Dialog*, and *Enjoyment*. It was applied to a science blog post and a science video on homeopathy to allow for advanced statistical analyses. Confirmatory factor analyses

indicated that quality is effectively assessed for both science communication formats.

All 15 subdimensions, originating from functional-system-oriented, normative-democracy-oriented, user-action-oriented, and science communication-specific perspectives, contributed substantially to the overarching quality factor. This confirmation underscores the importance of these subdimensions as key contributors to the audience's overall perception of science communication quality.

A major benefit of using multidimensional assessment scales such as the introduced QuASAP scale is their ability to illuminate the various subdimensions and their connections to various external concepts. Correlation analyses between the QuASAP scale and different external variables, representing typical target variables of science communication, revealed that different quality dimensions were associated with different science communication target concepts, such as interest and knowledge. This resulted in a nuanced depiction, enabling a detailed exploration of individual dimensions to reveal the extent of relationships present.

This also underscores the practical value of the QuASAP scale: it allows for the focused assessment of content on specific dimensions that are most likely to facilitate the achievement of science communication goals. The impact of quality subdimensions could be analyzed in future effect studies that consider the information provided in the science communication content. However, such analysis was not conducted in this study, as its primary aim was to introduce the multidimensional quality scale.

Naturally, the study has several limitations. First, the science issue chosen was homeopathy. We have neither controlled for the general interest in this issue nor for individuals' beliefs in this alternative medicine. The QuASAP should be used for other science issues and tested for validity. Moreover, we focused on social-media-based science communication formats as the research project was mainly interested in these due to their higher potential for public engagement. As much of the prior work included in the scale development was carried out in the context of expert discussions, we assume that the QuASAP should be able to be used for other content and formats as well, but this should be tested in future projects.

If the QuASAP scale were to be applied to other science communication formats and content, such as television programs, science exhibitions, barcamps, and others, it could facilitate the establishment of benchmarks for assessing the perceived quality of science communication. This would provide valuable insights for science communication practitioners to enhance their offerings and optimize them accordingly, resulting in significant practical benefits.

Besides the limitations based on researchers' decisions, it is further to mention that the validation of the scale relies on data from a single survey. Although the sample was representative of the German population regarding age, sex and education, sample effects cannot be excluded. Other studies with other samples need to use QuASAP to detect the robustness of the results.

Finally, as a first step, we were interested in developing a holistic assessment scale, including the societal-normative perspective, that can be applied to all science communication formats. However, using this instrument to learn more about the format-specific benefits and advantages for specific communication aims might also be possible. Here, we could not compare, for example, whether the level of entertainingness is higher in science videos than in text-based blog

posts as we had not controlled for the content but relied on field material. This could be a fruitful approach to learning more about the specific advantages of science communication formats and even channels.

In general, we aimed to highlight the relevance of the audience perspective with this introduction of the multi-dimensional quality assessment scale, and thus hope to see this reflected in future research.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MT: Writing – original draft, Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. JF: Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation. NW: Writing – review & editing, Project administration, Methodology, Data curation, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fcomm.2024.1384403/full#supplementary-material>

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