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Exploring impacts of participatory science communication on science, politics, and society

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Discussions on potential impacts of participatory science communication (PSC) formats on science, society, and politics would benefit from more empirical investigation. This article provides a systematic analysis of the perceptions of science communicators on the potential impacts of PSC on these different groups. The two basic questions are: What impact does PSC have on science, society, and politics? To what extent can these impacts be attributed to the different PSC communication formats? To answer these questions, 20 PSC projects implemented in the German Science Year 2022 were analysed. Semi-structured interviews with project coordinators revealed diverse potential impacts on science, society, and politics. While the impacts on science and society were predominantly assessed positively, impacts on politics were considered to be more case-specific and subordinate. Regression analyses indicate that these impacts can rarely be attributed to the PSC communication formats applied in projects. The results call into question global statements on the relevance of participation, and highlight the importance of different impact mechanisms for different groups in communication projects.

KEYWORDS

comparative case study, impact, mixed methods, models of science communication, participation

1 Introduction

The design of science communication is subject to ongoing discussion in communication research. Understood as the 'social conversation around science' (Trench and Bucchi, 2021), science communication can refer to various practices of how science and society interact with each other. While there are various ways to differentiate various formats of science communication, researchers increasingly differentiate these formats according to the level of participation in science communication and closely associated fields such as public engagement (e.g., Lewenstein, 2003; Wellcome Trust, 2011; Metcalfe, 2019, 2022). The level of participation refers to the degree of involvement of citizens in science communication activities and varies from low to high levels; low levels typically refer to unilateral information transfer of researchers with citizens, such as providing a website or publishing press releases; middle levels typically include bilateral interaction, such as discussions with and consultation of citizens; in high levels, citizens are actively engaged with researchers and can actively contribute to research activities (Wellcome Trust, 2011). These differentiations have resulted in three ideal-typical models of science communication, ranging from the classic deficit model of science communication focusing on unilateral knowledge transfer (science literacy) to dialogic models embracing bilateral information exchange (public understanding of science) to a participatory model of science communication calling for recommendations and co-decisions by the public in research activities (science in society) as well as a mix of these (Metcalfe, 2019, p. 46ff; Metcalfe et al., 2022). Consequently, participatory science communication (PSC) can be understood as a way of interaction between science and society at a level playing field, representing the power shift from science to society in academia (Metcalfe et al., 2022, p. 5).

This power shift represented in the different levels of participation and their representation in these three science communication models resonates well with the power shifts described with respect to different levels of participation in participatory research such as citizen science and transdisciplinary research, participatory science governance including the governance of science, and public participation in policy, planning, and governance. In these fields, researchers point to different levels of interaction between the public and decision-makers in science and politics; from unilateral information transfer to consultation and co-decision-making (Arnstein, 1969; Rowe and Frewer, 2005; Bora and Hausendorf, 2006; Schrögel and Kolleck, 2019; Haklay et al., 2021; Albert et al., 2023; Newig et al., 2023). In the field of participatory research, for instance, citizen science can include different levels of involvement, from the involvement in data collection in contributory citizen science to involving citizens throughout the research cycle in transdisciplinary approaches (Haklay et al., 2021).

These ideal-typical models of science communication result in diverse, yet empirically unsubstantiated assumptions on their potential impacts. On the one hand, research and practice increasingly hint at the potential positive impact of high levels of participation on different groups, including the participants themselves, researchers, and political decision-makers (Metcalfe et al., 2022; Roche et al., 2023). Examples are increasing innovation in science and research, the empowerment of citizens, democratization, or increasing legitimization through more knowledge of scientific methods and trust in scientific outcomes (Weingart et al., 2021; Gantenberg et al., 2024). These assumptions also resonate with other fields, such as transdisciplinary science (Wiek et al., 2014; Newig et al., 2019), citizen science (Fraisl et al., 2020; Wehn et al., 2021), participatory engagement in science and research (Evely et al., 2011), and political participation (Jager et al., 2020). They have also led to increasing promotion of PSC and science engagement in practice (Weingart and Joubert, 2019; Weingart et al., 2021; Metcalfe, 2022). In essence, this positive view of participation in different fields of research and practice is based on the assumption of 'better' impacts on the respective groups, supporting a 'the more the better' type of argument.

However, research has also emphasized that high levels of participation can be associated with specific implementation challenges, risks, and negative impacts on academia, politics, and society (Simis et al., 2016; Weingart et al., 2021; Gantenberg et al., 2024). Examples include issues of representation, power, lack of resources and skills for the implementation of participatory formats, and a lack of institutional incentives (Simis et al., 2016; Gantenberg et al., 2024). Again, the research findings resonate well with skeptical opinions on the role of transdisciplinarity in academic productivity (Newig et al., 2019; Jahn et al., 2022), the potential for diverse detrimental impacts of citizen science (Walker et al., 2021), and critiques of participation in the field of public policy (Cooke and Kothari, 2001; Irvin and Stansbury, 2004). Furthermore, research in different participatory fields demonstrates that the positive impacts of participation are subject to the actual design of participation (Bryson et al., 2013; Jager et al., 2020; Kirschke et al., 2023). The implementation of highly participative modes of science communication is also rare and not in line with the promotion of PSC and public engagement in its ideal-typical form (Simis et al., 2016; Weingart and Joubert, 2019; Metcalfe, 2022; Nerghes et al., 2022). In essence, and in contrast to proponents of positive relationships, critics in different fields of research tend to base their criticism on quantitative rather than qualitative arguments.

Against this background, this study aims to analyse perceptions of science communicators on the actual design and potential impacts of PSC on different priority groups, including science, politics, and society. The two basic questions are: What impact does PSC have on science, society, and politics according to science communicators? And to what extent do science communicators attribute these impacts to different PSC communication formats? We present a comparative case study approach, including 20 cases of science communication implemented in the German Science Year 2022 'Participate'. These cases are particularly well suited for analysing perceptions on potential PSC impacts in a comparative way, since they all aim to implement PSC under similar framework conditions such as the short length and small-scale funding scope of the project, while the actual spheres of implementation span a wide range of issues, including social, natural, and technical problems (Kirschke and Kosow, 2025). While addressing science communicators instead of the participants themselves is only an indirect measurement of impact, science communicator's assessments are particularly insightful as these actors typically have the most comprehensive knowledge of the participatory approach and their impacts in a specific project context (Sprinks et al., 2021; Kirschke et al., 2023).

Section 2 defines and operationalizes the key terms 'PSC' and 'impacts'. This section further elaborates on varying perspectives on the potential positive and negative impacts associated with quantitative and qualitative arguments. Section 3 introduces the comparative case study design, including 20 PSC cases. The section further introduces the mixed-methods approach to analyse these cases, including interviews with science communicators involving qualitative elements and accompanying surveys as well as the qualitative and quantitative methods used in the analysis. Section 4 presents the results, including the descriptive quantitative and qualitative results for the PSC formats used, their potential impact on priority groups, and a regression analysis to empirically assess whether and to what extent the expected impacts can be attributed to the specific PSC formats applied in the projects. In Section 5, we discuss the results in light of the ongoing PSC discussion and provide avenues for further research.

2 Conceptual and theoretical framework

2.1 Definitions of basic concepts

Science communication activities abound, as does the wish to evaluate the impact of these activities clearly. These impact measurements still face several challenges, including the actual definitions of emerging types of science communication activities and their impacts (Metcalfe, 2022; Ziegler et al., 2021).

Participatory science communication is a relatively new concept compared with informative and dialogic forms of science communication, resulting in diverse definitions in the literature (Bucchi and Trench, 2016; Metcalfe, 2019; Weingart et al., 2021; Ayure and Triana, 2022; Metcalfe et al., 2022). This study follows the understanding of Metcalfe et al. (2022), stating that 'participatory science communication happens when scientists and/or science communicators interact with various publics in a dynamic process in which different forms of knowledge and experiences are acknowledged, shared, valued, and negotiated, and where power relations are leveled' (Metcalfe et al., 2022, p. 5). Such involvement typically occurs at different stages of the participatory research process. In contrast to participatory research, PSC, however, integrates the public into research processes as a means to communicate science with the public and not necessarily as a means to implement joint research. Additionally, this study acknowledges that PSC can be implemented in different ways by mixing lower and higher levels of participation in communication activities (Metcalfe, 2019). Based on the literature in science communication and related fields (e.g., Lewenstein, 2003; Wellcome Trust, 2011; Schrögel and Kolleck, 2019; Metcalfe et al., 2022), these levels typically range from low levels (different modes of unilateral information sharing) via middle levels (different modes of dialogic interaction) to high levels (actual provision of research recommendations and joint decision-making in research). Therefore, this study further understands PSC as a multidimensional continuum between two extremes, from low levels of more informative science communication to high levels of participatory models of science communication.

The concept of **impact** is widely used in participation-related analyses in the social sciences (e.g., Bornmann, 2013; Jager et al., 2020; Wehn et al., 2021; Ziegler et al., 2021). Yet, the societal impact of science and science communication, more particularly, is still a vague, and under-researched concept (Spaapen and Van Drooge, 2011; Bornmann, 2013; King et al., 2015; Mayne, 2015; Ziegler et al., 2021; Somerwill and Wehn, 2022). This study understands the impact of science communication widely, including different stages of effects from outputs, via outcomes related to the capacities of priority groups, to wider societal impacts. We further understand impact as a multidimensional continuum between two extremes, from low to high levels of impact on priority groups. Given the different motives for science communication, priority groups for science communication can be diverse and include different actors in academia, politics, and society. Academia typically encompasses professional researchers in various scientific disciplines located at universities or — in some countries — also state-funded non-university research entities. Politics can encompass all types of actors in the political-administrative system, such as politicians or administrative bodies, from local to national and international levels. Society can refer to different mini-publics, including various age groups, genders, knowledge levels, and interests in science (Bucchi and Trench, 2016; Schäfer et al., 2018; Humm and Schrögel, 2020; Weingart and Joubert, 2019).

Figure 1 provides an overview of the multidimensional concept of 'PSC' and 'Impact'. The figure shows that each PSC level (e.g., unilateral information transfer) can affect all three impact groups (e.g., society). The figure further shows that each level of science communication and impact group can have lower or higher scores. This is in line with research highlighting that both participatory science communication and impact categories can be present to different degrees in individual science communication formats (e.g., Metcalfe, 2019; Metcalfe, 2022; Metcalfe et al., 2022).

2.2 Relationships between science communication and impacts

The relationship between PSC and impacts on academia, politics, and society has been subject to discussion in the fields of science communication and public engagement, as well as in different fields of participatory research, participatory science governance, and public policy. Consequently, there are diverging views on the impact of PSC

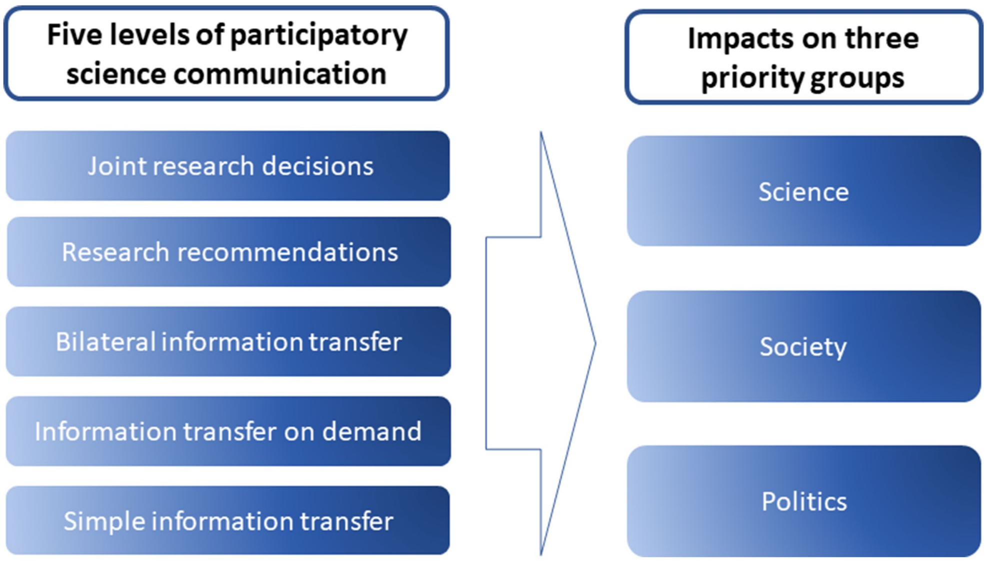

FIGURE 1
Conceptual model including levels of participatory science communication and impacts on priority groups. The arrow represents the diverse possible relationships between all five levels of participation and all three priority groups. Different shades of blue represent different levels of prevalence of the respective category – from low, via middle to high levels of the respective participatory science communication level and impacts on priority groups. Source: own representation.

on diverse priority groups considered. These diverging views are typically based on different types of arguments, including quantitative arguments hinting at effect size (e.g., reach of people, number of scientific outputs) and qualitative arguments hinting at the quality of effects (e.g., increase in knowledge of those addressed, better research outputs). The following paragraphs describe both positive and negative relationships based on these quantitative and qualitative arguments.

On the one hand, different fields of research related to participation such as science communication and participatory research argue for a potentially positive relationship between well-designed PSC and its impact on academia, politics, and society. This positive relationship is often based on qualitative arguments (i.e., better impacts) rather than quantitative effects (i.e., more impacts). The general argument is that PSC may enable mutual understanding and trust, knowledge exchange, and, therefore, an increase in knowledge and evidence-based transformative action in science, society, and politics (Metcalfe et al., 2022; Gantenberg et al., 2024). In terms of academia, based on citizen's participation in science communication and research, the academic sector can receive innovative ideas from these citizens, which can ultimately result in adjustments to research questions and approaches (Holford et al., 2023; Gantenberg et al., 2024). In terms of politics, well-designed participatory approaches to science communication may enable more specific advice and, therefore, better use of scientific expertise in policy design and implementation. In terms of society, the direct exchange among researchers and citizens and the experience of participatory research would, in particular, create trust in scientific processes and outcomes, and therefore, also result in better acceptance of science knowledge compared with informative and dialogic forms of communication only (Gantenberg et al., 2024). These expectations regarding the positive impacts of PSC are closely connected to the expectations of related fields of practice, such as public engagement, various fields of participatory research, and political participation in public policy (Evely et al., 2011; Wiek et al., 2014; Newig et al., 2019; Fraisl et al., 2020; Jager et al., 2020; Wehn et al., 2021).

On the other hand, different fields of research hint at a potentially negative relationship between PSC and impact. In contrast to the description of positive impacts, this negative relationship is often based on quantitative arguments (less impacts) than qualitative effects (worse impacts). A key argument is that high levels of participation can also be associated with specific implementation challenges, risks, and negative impacts on groups in the public, in politics, and in academia (Stilgoe et al., 2014; Simis et al., 2016; Weingart et al., 2021; Gantenberg et al., 2024; Kirschke et al., 2024). In terms of academia, research has hinted at high transaction costs, including temporal, financial, and human resources, resulting in a lack of resources for successful implementation or in binding resources that could otherwise be invested in research activities (Kirschke et al., 2024). In close relation to this argument, research has continuously hinted at a lack of resources, such as time and financial resources for inter- and transdisciplinary research (Bromham et al., 2016, Bessert-Nettelbeck et al., 2023). Further, comparative research has shown that inter- and transdisciplinary research is likely to lead to fewer peer-reviewed publications than research implemented in a more disciplinary matter (Leahey et al., 2017; Newig et al., 2019; Jahn et al., 2022). In terms of politics, research in fields such as political communication and evidence-based policy design has continuously hinted at the complexities of the science-policy interface, questioning the substantial impacts of knowledge transfer on policy processes (Scheufele, 2014; Cairney, 2016; Cairney and Kwiatkowski, 2017; Parkhurst, 2017). From this perspective, the substantial impacts of PSC on politics may be limited. Likewise, research on the effects of participation on public policy has questioned the impacts of participation on policy design and hinted at diverse implementation issues, including high costs of participation (Cooke and Kothari, 2001; Irvin and Stansbury, 2004). Finally, in terms of society, societal knowledge gains may be lower in PSC than in more traditional informative and dialogic formats, given the emphasis on processes and exchange of opinions rather than the actual transfer of scientific knowledge. In addition, owing to the high transaction costs, participatory formats may not necessarily be implementable at larger scales, thus reducing the reach of such formats. Furthermore, research on participatory research, such as citizen science, has hinted at the potential of diverse detrimental impacts of citizen science on participating citizens (Walker et al., 2021).

Hence, there is an ongoing controversial debate on potential impacts of PSC on science, politics, and society. And certainly, more empirical investigation and evidence would enhance the discussion.

3 Methods

3.1 Comparative case study

The study follows a comparative case study design with 20 communication projects implemented within the German Science Year 2022 'Participate' to explore science communicators´ perspectives on PSC impacts. This approach of analyzing 20 cases reduces potential biases of both single and low-N case studies and, thus, enables the generating of lessons learned beyond individual or a small set of cases (see also Beckers et al., 2010). This particularly holds true as the analysis of these 20 cases allows qualitative information to be combined with standardized statistical procedures, as will be described in sections 3.2 and 3.3.

The German Science Year 2022 'Participate' was a funding initiative of the German Federal Ministry of Education and Research (BMBF), which aimed to advance dialogue between science and society through a needs-based approach. Citizens were asked to pose questions, while researchers and political decision-makers addressed these questions in their discussions with citizens, research activities, and research policy design. As such, the Science Year 2022 'Participate' understands citizens as 'equal partners' in research, which can influence research and research policy alike (BMBF, 2024; Kirschke and Kosow, 2025).

Within this Science Year 'Participate', 25 individual projects have been funded of which 23 have been contacted and 20 agreed to be included in this analysis (BMBF, 2022; Kirschke and Kosow, 2025; Supplementary material 1). We only asked 23 projects to participate in this study as the two remaining projects had different framework conditions (e.g., longer project duration) and were, thus, not comparable. The selected projects are further particularly interesting to study as they are most similar in terms of our research focus and most different in terms of the design and focus of the projects. In terms of similarity, all projects explicitly focus on the design and implementation of PSC formats and how these affect different priority groups. The projects were in fact funded to develop, apply, and evaluate innovative PSC formats to induce change in science, society, and politics, and thus perfectly fit with the focus of this study (BMBF, 2022). Second, the overall framework conditions of these projects have been similar, including the rather short length of the projects (approximately 11 months), the small-scale funding scheme (through BMBF within the Science Year funding scheme), and their overall contribution to collecting questions from citizens for future research (BMBF, 2022). This enables a direct comparison between the projects since shorter, small-scale projects arguably have probably lower and different impacts than longer, large-scale projects. Third, the German government had high expectations regarding the impact of these projects in terms of trust building, while actual studies substantiating these impacts are still lacking (Peters et al., 2020). At the same time, these projects include different types of formats (e.g., virtual and on-site, discussion or action-based such as in workshops or in experience-based learning), different age groups (e.g., younger and elderly persons such as school children or old age pensioners), in various spaces (e.g., schools, universities, touristic places, or spaces of everyday life). The projects also addressed different types of topics, ranging from nature-related to more technical and social questions, such as climate change, sustainable resource management, artificial intelligence, digitalization, education, social integration, and urban development. This variety in formats, age groups, spaces, and themes allows understanding potential impact patterns of projects across the individual focus of the projects. This, again, potentially increases the transfer of results to other science communication projects (Kirschke and Kosow, 2025).

3.2 Data collection

Data collection activities included 20 online interviews with science communicators of the 20 science communication projects, taking place between 24.11.2022 and 26.01.2023, each lasting 90 min on average. These interviews were voluntary and all interviews provided verbal informed consent to participate in the study. The publication of interview results was agreed upon provided that data were anonymized. Therefore, no direct attribution of the study results to single projects, including paraphrasing or citations of specific project results is possible.

The interviewer prepared for the interviews through a preliminary document analysis, including a detailed screening of project websites and related documents. The actual interviews were conducted with the coordinators of these projects, who acted both as designers and main implementers, and thus as experts in science communication activities. Interviews with project coordinators were conducted both bilaterally (with one coordinator) and multilaterally as group interviews (with two coordinators), depending on the number of coordinators per project or the availability for an interview. Expert interviews are a standard approach in social science analysis (Kaiser, 2014). Likewise, understanding project coordinators as experts on the impact of participatory approaches is increasingly being recognized (Sprinks et al., 2021; Kirschke et al., 2023). While this approach does not allow for direct conclusions on the actual impacts of participatory formats, it provides key insights from the perspectives of those actors who typically have the most comprehensive knowledge of the participatory approach and their impacts in a specific project context (Sprinks et al., 2021; Kirschke et al., 2023).

The interviews were conducted by the first author — a social scientist experienced in the design, implementation, and analysis of semi-structured interviews (e.g., Kirschke et al., 2017). The interviews were based on a semi-structured guiding questionnaire (see Supplementary material 2) that included both qualitative open questions typical of expert interviews (Kaiser, 2014) and an accompanying survey with structured questions using Mentimeter, allowing for the comparability of the 20 qualitative interviews (see also Porst, 2014). The interviews started with general introductory remarks (welcome, round of introduction, project, and interview information), general questions related to the project (verification of time and place), and the project design phase (inter- and transdisciplinarity in the project design). The interviews then included questions related to five parts: (i) the problem area, (ii) the goals of the project, (iii) the PSC approach, (iv) the barriers encountered while implementing these activities and the solution strategies applied, and (v) the perceived impact on society, science, and policy. The interview was then closed, with concluding remarks by both the interviewees and the interviewer (see also Kirschke and Kosow, 2025). It is important to note that this study only reports the results of parts (iii and v), that is, the actual PSC approach and its impacts.

In terms of part (iii) of the participatory approach, the main goal was to understand the degree to which different levels of participation are applied in the projects. To this end, the interview included open questions on the actual format, as well as structured survey questions on the level of participation. Questions on the project's approach to science communication were first formulated in an open manner, allowing for maximum flexibility in answering the questions. The science communicators were then asked to describe and indicate the PSC formats applied in their projects along a five-dimensional concept, reflecting the participation level and ranging from low to middle and high levels of participation. These five PSC formats are: (i) simple information transfer, (ii) information transfer on demand, (iii) bilateral information transfer, (iv) provision of recommendations, and (v) joint decision-making on research. These five formats were chosen as they closely align with literature on the measurement of participation (see Section 2.1) and the specific needs of the science year 'Participate', which put special emphasis on information transfer on demand. The five formats of participation were further analysed on a 1–4 scale each, with 1 indicating low and 4 indicating high relevance of the respective participatory format in the respective project.

In part (v) on the impact of projects, the interviewer asked about the project's potential impact on three groups: science, society, and politics. Questions were again formulated in an open manner, allowing for maximum flexibility in answering the questions. The science communicators were asked to describe and indicate the extent to which the three groups were potentially affected by science communication activities. The answers could be provided for the three groups separately and on a scale from 0 to 4, with 0 indicating no impact and 4 indicating a high positive impact. It is important to note that this scale allowed, but did not explicitly prompt interviewees to weigh quantitative and qualitative arguments regarding impacts. This allowed us to explore how impactful the participatory science approach was judged overall including both quantitative and qualitative perspectives without forcing a specific impact understanding on the site of the interviewees whose project goals may have differed in terms of these qualitative or quantitative considerations.

As a result, we get aggregated scores on a positive Likert scale, following the assessments and perceptions of the project's science communicators that were interviewed. The numbers for PSC formats represent their perception on the extent and intensity of these formats used in the specific projects whereas numbers related to the impact on priority groups provide the perception of these communicators on potential positive impacts of their specific project on science, politics, and society.

3.3 Data analysis

The numerical data from the survey are summarized in Supplementary material 3. In the first step, we analysed the numerical data both on the answers to the PSC formats used and the expected impacts on the three priority groups by applying basic descriptive statistics in Excel. We calculated the percentage of each answer category, median values, lower and upper quartiles, and minimum and maximum values to obtain a general impression of the data-set. Boxplots helped to visualize the distribution of the answer categories.

In the second step, the numerical data were analysed using standard statistical methods using SPSS (version 29, Brosius, 2018; Backhaus et al., 2018). The analysis included a factor analysis of both (i) the five participatory science formats used, and (ii) the expected impacts on the three groups. Factor analysis was used to check whether the format and impact variables could be meaningfully reduced to more comprehensive format factors and impact factors. Multiple linear regression analysis was implemented to identify the potential impacts of PSC formats (independent variables) on the potential impacts on different priority groups (dependent variables). We formulated a regression model for each impact variable (science, society, and politics) and checked the explanatory power of the overall model (corrected R squared, significance level) and individual regression coefficients (beta coefficients, significance level). To better understand the regression models and sharpen potential impacts, we further changed the regression models, reducing the number of independent variables and using the SPSS backward procedure. The sample size of the quantitative analysis is certainly limited, but the statistical methods, and notably testing procedures, were rigorously applied to avoid over- and/or misinterpretation. Hence, we think that the quantitative analysis gives some empirical evidence on the impact perceptions of PSC.

In the third step, a qualitative analysis was applied to the survey results by the first author — a political scientist with interdisciplinary research experiences in the participatory sciences. The qualitative analysis first included an automated transcription of the interview recordings using SONIX transcription software. These automatic transcripts were then thoroughly cross-checked, resulting in transcript corrections. The written transcripts were then coded in two consecutive phases using the MAXQDA software (Mayring, 2014). The first coding phase aimed to identify the key categories related to the five formats of participatory science communication and their impact on the three groups. Therefore, the main and overarching coding categories are consistent with the conceptual framework presented in Figure 1. The second coding round aimed to fine-tune the results based on a second reading. This phase focused on building sub-categories of example activities and impacts. The respective (sub-) codes (identified categories) and coding (text segments) were extracted from the MAXQDA platform and further condensed to provide a systematic overview of the qualitative data across the 20 cases. The presentation of the respective results in the results section abstains from direct citations and descriptions of individual projects to secure the assured anonymity of the interviewees. Furthermore, the 20 interviews were pseudo-anonymized, attributing a number of 1–20 to each of the projects, to ensure qualitative research standards without further traceability to individual projects that are ordered in alphabetical order in Supplementary material 1.

4 Results

4.1 Participatory science communication formats

4.1.1 Numerical data

The descriptive analysis of the survey results revealed that different PSC levels have been implemented. Formats representing rather low levels of participation scored rather high, meaning that they were more prevalent in the data set, whereas formats representing rather high levels of participation scored rather low, meaning that they were less prevalent in the data set. Technically speaking, the format of 'Information transfer on demand' scored highest (median = 3.5), closely followed by 'Bilateral information transfer' (median = 3.3), and 'Simple information transfer' (median = 3.0). Providing 'Research recommendations' was rather unlikely (median = 2.0), and 'Joint research decisions' were almost completely excluded from the dataset (median = 1.3) (see Figure 2; Supplementary material 3).

Subsequent factor analysis (Supplementary material 3) suggests the reduction of the five participation format variables to two format factors (Eigenvalue above 1), with factor one including 'Bilateral information transfer' and 'Research recommendations', and factor two including 'Simple information transfer', 'Joint research decisions', and 'Information transfer on demand'. However, the Kaiser-Meyer-Olkin Measure (0.587) and Bartlett's test (0.920) are not convincing, advising against the reduction of the participation variables to fewer participation factors. Thus, while a combination of these different formats is not necessarily implausible, we concluded that the five defined format variables properly describe the format dimensions for PSC in our dataset. We thus used these five variables in the subsequent regression analysis.

4.1.2 Qualitative data

The interviewees provided qualitative information and examples of PSC activities in the projects (see Table 1). Additional qualitative results regarding the relevance of the respective science communication formats are provided in Supplementary material 4, Part 1. Due to the rather large number of cases (20) and the ensured anonymity of results, this section does not provide specific descriptions or citations of individual project activities.

16 projects shared additional information on Simple information transfer, including information on example activities and further information (Interview (IV) 02, 03, 05, 06, 08–16, 18–20; Supplementary material 4, Part 1). Out of these 16 projects, 12 shared

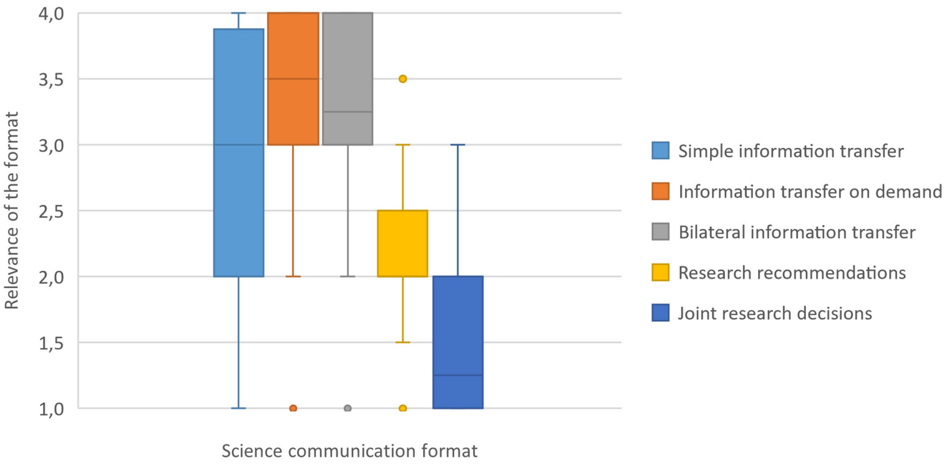

FIGURE 2
Participatory science communication formats. Depicted are the median levels for 5 types of formats, representing low to high levels of participation. Source: own representation.

TABLE 1 Results of the qualitative analysis for participatory science communication formats: example activities.

Participatory science communication formats	Example activities
Simple information transfer	Presentations, podcasts, movies, exhibitions, topic setting for events, information material
Information transfer on demand	Design and adaptation of communication activities based on citizens' interests/questions, answering questions as part of the implementation of communication activities
Bilateral information transfer	General descriptions of bilateral information transfer, specific descriptions of formats used for bilateral information exchange
Research recommendations	Process-related recommendations, activity-related recommendations, project-specific recommendations, recommendations via the overarching campaign "Ideenlauf", further recommendations
Joint research decisions	Project-specific decisions, decisions with regard to follow up projects, decisions via the campaign "Ideenlauf"

Source: own representation.

information on the types of activities implemented (IV 02, 05, 06, 08, 11, 13–16, 18–20). Interviewees highlighted introductory presentations by scientists at events/workshops (in-depth or low-threshold, using diverse innovative formats) (8 cases: IV 05, 06, 08, 11, 16, 18–20), podcasts (2 cases: IV 13, 18), movies (1 case: IV 15), exhibitions (1 case: IV 11), setting topics for events (1 case: IV 14), and sharing information material on the science year and the projects (e.g., through posters, flyers) (1 case: IV 02).

19 projects shared additional information regarding Information transfer on demand, including information on example activities and further information (IV 01–16, 18–20; Supplementary material 4, Part 1). Out of these 19 projects, 17 projects shared information on the types of activities implemented (IV 01–13, 15, 16, 19, 20). The interviewees highlighted two types of example activities: first, activities included the design and adaptation of communication activities based on citizens' interests/questions (e.g., discussing topics that were part of the school curriculum, selecting topics for debates/workshops based on the relevance of topics in a specific region, using questions for the development of workshops, the further development of games, the construction of topic-specific streams, or for the development of science seeing tours) (7 cases: IV 02, 05–08, 10, 12); and second, activities included answering questions both face-to-face and online, synchronous and asynchronous as part of the implementation of communication activities (e.g., during the implementation of workshops; in the course of simulation games; in the course of streaming activities in the chat; on a specific online platform or website; via social media such as Tiktok, Instagram, and podcasts, after experience-based learning activities; and after watching a movie) (15 cases: IV 01, 03–06, 08–13, 15, 16, 19, 20).

20 projects shared additional information on Bilateral information transfer, including information on example activities and further information (IV 01–20; Supplementary material 4, Part 1). Out of these 20 projects, 18 shared information on the types of activities implemented (IV 01–11, 13–17, 19, 20). Interviewees highlighted two types: First, they mentioned general descriptions of bilateral information transfer (e.g., hinting at dialogue, conversations, exchanges, discussions, communication on an equal footing, joint reflections, and co-design and co-creation; in specific phases of the project or across phases) (11 cases: IV 03–07, 10, 11, 15–17, 20); and, second, interviewees provided specific descriptions of formats used for bilateral information exchange (e.g., bilateral information exchange via citizen science activities, as part of study projects, at workshops including specific formats such as object design or fishbowls, the exchange at excursions and at 'science seeing' tours at citizen's councils, via online platforms such as Twitch or specific platforms for

the exchange of spatial information, as well as commenting on podcasts) (9 cases: IV 01, 02, 06–09, 13, 14, 19).

18 projects shared additional information on Research recommendations, including information on example activities and further information (IV 02, 03, 05–20; Supplementary material 4, Part 1). 15 out of these 18 projects provided further explanatory information, such as on the types of activities that have been implemented (IV 02, 05–15, 17, 19, 20). Interviewees highlighted the following types of recommendations: (i) process-related recommendations (impulses from civil society partners in the project) (1 case: IV 02), (ii) activity-related recommendations (i.e., impulses for participating researchers provided by citizens during the respective project activities, e.g., at discussion rounds, via chats) (6 cases: IV 07–09, 11, 15, 19), (iii) project-specific recommendations (i.e., the possibility of impulses from the overall implementation and evaluation of the project activities of further research and communication projects, but also questioning of important impulses from the respective projects) (8 cases: IV 02, 05–07, 09, 10, 12, 14), (iv) recommendations via the campaign "Ideenlauf" (4 cases: IV 10, 11, 13, 15) (e.g., potential of impulses for research, but also questioning of key impulses), as well as (v) further recommendations (e.g., recommendations for different types of actors such as political decision-makers) (2 cases: IV 17, 20).

15 projects shared additional information on Joint research decisions, including information on example activities and further information (IV 02, 03, 05, 06, 08, 09, 11–16, 18–20; Supplementary material 4, Part 1). Out of these 15 projects, eight shared further explanatory information and example activities (IV 02, 05, 06, 09, 11–14). Interviewees referred to (i) project-specific decisions (mostly denial of joint decisions in the project, in part the goal of influencing joint decisions, in part joint decisions with regard to specific activities such as student projects) (7 cases: IV 02, 05, 09, 11–14), (ii) decisions with regard to follow up projects (goal of joint decisions in the future, planning of projects in the future) (3 cases: IV 05, 06, 09), and (iii) decisions via the campaign "Ideenlauf" (e.g., potential of joint decisions via the compaign) (2 cases: IV 02, 05).

4.2 Participatory science communication impacts on priority groups

4.2.1 Numerical data

The descriptive analysis of the survey results reveals that the expected overall quantitative and qualitative impacts of the projects on the three groups varies significantly between these groups ('Society', 'Science', and 'Politics'). The expected impact on society and science scored the highest (both median = 3.0), whereas the impact on politics scored the lowest (median = 1.0) (see Figure 3; Supplementary material 3).

Subsequent factor analysis (Supplementary material 3) again suggests the reduction of the three impact variables to two impact factors (Eigenvalue above 1), with factor 1 including impacts on science and society and factor 2 representing impacts on politics. As for the factor analysis of format variables, however, the Kaiser-Meyer-Olkin Measure (0.470) and Bartlett's test (0.101) were not convincing, questioning the reduction of the three impact variables to these two impact factors. We again concluded that the three defined impact

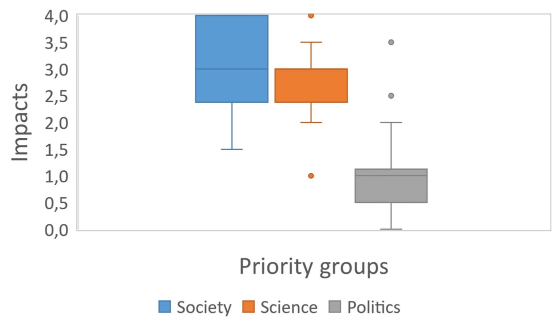

FIGURE 3
Participatory science communication impacts. Depicted are the median levels for the 3 groups 'Society', 'Science 'and 'Politics'. Source: own representation.

variables properly describe the impact dimensions for PSC and we used these variables to define three corresponding regression models in the subsequent regression analysis.

4.2.2 Qualitative data

The interviewees provided further qualitative information on the relevance of the respective impacts as well as examples. The results are presented in Table 2. Additional qualitative results regarding the relevance of the impacts are provided in Supplementary material 4, Part 2. Due to the rather large number of cases (20) and the assured anonymity of results, this section does not provide specific descriptions or citations of individual project results.

Twenty projects shared additional information on impacts on Science, including information on example impacts and further information (IV 01–20; Supplementary material 4, Part 2). Interviewees first highlighted impacts related to science communication, specifically (i) advancing science communication among scientists (13 cases: IV 01, 05–08, 10, 13, 15–20), (ii) the continuous use of the developed formats and lessons learned (3 cases: IV02, 12, 17), and (iii) the development of follow-up science communication projects (3 cases: IV 01, 09, 14). The interviewees further mentioned impacts on research, including (i) direct scientific utilization of project results as part of presentations and publications (3 cases: IV 03, 10, 16), (ii) direct scientific learning including new knowledge on research areas, new research questions, research recommendations, and uptake of research interests of societal actors (4 cases: IV 04, 05, 09, 16); (iii) more implicit learning in various dimensions such as out-of-the-box thinking, further discussion and debate, and peer-to-peer learning (4 cases: IV 05, 10, 11, 14), and (iv) interdisciplinary networking (2 cases: IV 08, 12). In addition, the impacts of teaching were mentioned, specifically, the integration of findings into teaching (2 cases: IV 10, 12).

Twenty projects shared additional information on impacts on Society including information on example impacts and further information (IV 01–20; Supplementary material 4, Part 2). Interviewees first further specified the respective priority group within society to attribute impacts to, emphasizing the actors participating in the respective activities (20 cases: IV01–20). Interviewees also often clarified the respective reach, providing in part numbers or general assessments of low or high reachability via

TABLE 2 Results of the qualitative analysis for impacts on three priority groups: Example impacts.

Priority groups	Example impacts
Science	Science communication: advancing science communication, continuous use of knowledge and follow up projects; Research: direct scientific utilization of project; direct scientific learning, implicit learning, interdisciplinary networking; Teaching
Society	Further specifications of priority group and reach; process-related outcomes such as increase in learning/knowledge; further outcomes such as raising interests; potential impacts on actions; sustainability issues
Politics	Further specifications of priority group; direct and indirect impacts at different levels

Source: own representation. *Total projects can exceed 20 because of the possibility of multiple impacts per group.

their respective activities, such as workshops or social media (12 cases: IV 01, 02, 06–10, 13, 16–18, 19). In terms of example impacts, interviewees first mentioned specific process-related outcomes, starting with direct (emotional) reactions including interest, openness to conversations, curiosity, fun, and self-efficacy (16 cases: IV 04–13, 15–20). Interviewees also mentioned an increase in learning/knowledge as a process-related outcomes, including both content-related knowledge and scientific process knowledge (10 cases: IV 01, 07, 08, 10, 12–15, 18, 19). Interviewees also mentioned further outcomes (post events), including increased interest in the respective scientific processes and contents (4 cases: IV 05, 06, 16, 18), as well as further reflection in the aftermath (2 cases: IV 03, 16), as well as a better connection between science and society based on the activities (IV 10, 19). However, further long-term impacts on actions have been discussed less frequently (IV 17, 18). Finally, sustainability issues were very prominent, typically hinting at potential larger impacts based on existing products or in the case of follow-up activities (7 cases: IV 04, 08, 09, 12–14, 17).

Twenty projects shared additional information about their impact on Politics including information on example impacts and further information (IV 01–20; Supplementary material 4, Part 2). Out of these 20 projects, 19 shared information on example impacts on politics (IV 01–17, 19, 20). Interviewees first specified the respective priority group within politics, referring here mostly to the state level (11 cases: IV 03–05, 07, 09, 10, 13–16, 20), local level (nine cases: IV 04–07, 13, 14, 19, 20), and federal state/regional level (three cases: IV 02, 08, 15). Impacts at the state level mostly refer to the potential impacts of collected topics and questions on research policy, as well as a potential lack of these impacts (9 cases: IV 03–05, 07, 09, 13, 14, 16, 20). Further impacts at the state level are the potential impacts of discussions with politicians (IV 10) and the impacts of the project on policies, including educational policies (1 case: IV 15). At the local level, interviewees highlighted connections and contributions to local political issues and topics (5 cases: IV 01, 07, 14, 17, 20), new perspectives based on discussions (two cases: IV 02, 08), local networking with politicians (3 cases: IV 04, 06, 17), and spill-over effects referring to the interests of other citizens to replicate respective activities (1 case: IV 07). At federal state level, discussions and new perspectives were highlighted (2 cases: IV 02, 08). Further, interviewees mentioned more overarching, indirect impacts on politics including interests by political organizations shown by respective requests (1 case: IV 12), impulses for politics through the engagement of involved civil society actors (3 cases: IV 11, 14, 17), the promotion of democracy (1 case: IV 01), new perspectives on political topics among involved citizens (1 case: IV 05), and influence on electoral decisions (1 case: IV 10). In addition, one project highlighted the inverse case, hinting at the positive impact of politics on the awareness of the science communication project (1 case: IV 15).

4.3 Impacts of participatory science communication formats on different priority groups

The potential impact of PSC formats on different groups was analysed using regression analysis. We have formulated a linear regression model for each impact variable 'Science', 'Society and 'Politics', depending on the five independent PSC format variables (see Table 3).

The explanatory power of the overall model for the impact variable 'Science' is rather low, with an explained variance of about 22%. The corrected R squared (−0.064) was poor, and the result was not significant (0.585). Looking at the regression coefficients, we calculated beta coefficients to better compare the magnitude of the potential impacts for the different format variables. We obtain low to medium positive and negative regression coefficients, but they are not significant. Hence, there is no statistical evidence based on our survey that the defined PSC format variables as a group or individually would have an impact on 'Science'.

However, backward regression may help to better understand the formulated model and reveal potential relationships. We used the SPSS backward procedure to reduce the independent format variables step by step in the regression model. The results are presented in Supplementary material 3. In fact, the variable 'Information transfer on demand' and, to a less degree, the variable 'Research recommendations' gain importance in a reduced model. The coefficients are rather stable in the various regression models and indicate a considerable positive impact on 'Science', in particular for 'Information transfer on demand'. The beta coefficient for this variable in the 1-variable-model is .406 and is also almost significant at a 5%-level (0.076). We do not want to stress the statistical result, but suggest that the potential positive impact of 'Information transfer on demand' on 'Science' deserves special attention in future research.

The explanatory power of the overall model for the impact variable 'Society' is also low, with an explained variance of about 17%. The corrected R squared (−0.122) is poor and the result was not significant (0.711). The beta coefficients mostly indicate low to medium negative values that are not significant. Again, there is no statistical evidence based on our survey that the defined PSC format variables as a group or individually would have an impact on 'Society'.

The backward regression results are presented in Supplementary material 3. These results only provide a few

TABLE 3 Results of regression analysis for participatory science communication impact variables.

Independent format variables	Regression model		
	Science	Society	Politics
Simple information transfer	0.045 (0.856)	−0.107 (0.677)	0.148 (0.534)
Information transfer on demand	0.398 (0.126)	0.158 (0.541)	−0.137 (0.564)
Bilateral information transfer	−0.062 (0.807)	−0.039 (0.881)	0.164 (0.500)
Research recommendations	0.216 (0.412)	−0.162 (0.547)	−0.130 (0.600)
Joint research decisions	−0.159 (0.539)	−0.300 (0.266)	0.485 (0.062)
Model indicators			
R squared	0.216	0.173	0.294
Corrected R squared	−0.064	−0.122	0.042
Significance level	0.585	0.711	0.373

Beta coefficients with significance levels in brackets, model indicators. Source: own representation.

additional insights. The overall regression and all beta coefficients remained insignificant for all reduced models. Possibly, the considerable negative regression coefficients for 'Joint research decisions' and 'Research recommendations' in their potential impact on 'Society' would deserve special attention in future research.

Finally, the explanatory power of the overall model for the impact variable 'Politics' is slightly higher as compared to the impact variables 'Science' and 'Society', with an explained variance of about 29% whereas the corrected R squared (0.042) remains poor and the result is also not significant (0.373). The beta coefficients have low to medium negative and positive impacts that are not significant, with the exception of the format variable 'Joint research decisions'. The analysis shows a comparably high positive coefficient (0.485) for this variable which is almost significant (0.062) at a 5%-level. With the exception of this variable, there is again little statistical evidence that the defined other PSC format variables as a group or individually would have an impact on 'Politics'.

The backward regression results are presented in Supplementary material 3. The reduced regression models confirm the comparably high positive coefficient for the variable 'Joint research decisions' at a high significance level. This PSC format variable in its potential impact on 'Politics' would, definitively, deserve special attention in future research.

5 Discussion

This paper analysed potential PSC impacts on science, society, and politics. Acknowledging that different assumptions on the impact of participation can be associated with quantitative or qualitative arguments, the study takes an explorative approach, considering both quantitative and qualitative arguments for impacts based on the respective perceptions of science communicators. The results first show that the 20 projects analysed in the study implemented mixed formats of science communication, with formats representing rather low levels of participation such as scientific presentations and answering citizens' questions being more prevalent than formats representing rather high levels of participation such as the uptake of citizens' knowledge in scientific processes. The analyses then revealed that the expected impact of the projects varies significantly between the three groups of 'society', 'science', and 'politics', with higher and — as the qualitative analysis has shown — also much more diverse expected impacts on society and science than on politics. Regression analysis then questioned whether the three impact dimensions would be significantly influenced by the five PSC formats, with significant results only in the reduced models and for a few variables and potential impacts.

The lack of significant results with respect to the five PSC formats on their potential impacts on science, politics, and society does not allow for clear conclusions in the controversial debate on the positive and negative relationships between the variables. However, the results of the regression (including backward regression) and related qualitative findings indicate potential relationships that could be addressed in follow-up analyses. In terms of impacts on science, the 1-variable-model showed that the explanatory power of the variable 'Information transfer on demand' is comparably high (0.406), with a high significance level (0.076). This is in line with the projects' emphasis on delivering science communication activities that represent this specific level of interaction (with 22 examples in 20 projects, see Section 4.1.2). Together, this suggests that lower levels of participation that are however particularly prevalent may be associated with a higher impact on science than higher levels of participation that are less prevalent. Likewise, in terms of impacts on society, the 1-variable-model showed that the negative impact of 'Joint research decisions' could be comparably high (−0.349), with a questionable significance level (0.132). This finding comes with a rather low number of example activities related to joint research decisions (with 12 examples in 20 projects). Taken together, this may suggest that higher, but less prevalent levels of participation may be associated with lower impacts on society than lower, but more prevalent levels of participation. Finally, and most importantly, in terms of impact on politics, the 1-variable-model showed that the beta coefficient of the variable 'Joint research decisions' is comparably high (0.482) and also significant (0.031). From a qualitative perspective, this comes with example activities related to the collection of citizens' questions as a means of influencing research policy. Science communicators, in fact, often argued that joint decision-making was mainly relevant in the science year 'participate' at a more general, and not necessarily project-specific level, focusing on the potential effects of the collection of research questions as a means to jointly decide on future research avenues at policy level. This suggests that a high level of participation aimed at affecting research policy may be associated with higher levels of political impact.

Although these results are based on limited statistical and qualitative evidence, they are not implausible. The high impact of the manifold activities of information transfer on demand for science suggests that information exchange adapted to the needs of the respective groups is more important than broad information campaigns. This is in line with the basic idea of the science year

'Participate' which promoted the collection of questions as a means to generate new research ideas connected to the interests of societal actors (BMBF, 2024). It is also plausible that unilateral sharing of information does not have significant impacts on scientific actors, as there is no feedback loop. However, the lack of significant relationships between activities demonstrating higher levels of participation ('Bilateral information transfer', 'Research recommendations', and 'Joint research decisions') and impacts is interesting given the strong arguments for either positive or negative impacts of PSC in the science communication literature (Weingart et al., 2021; Holford et al., 2023; Gantenberg et al., 2024) and related literature in various fields of participatory research (e.g., Evely et al., 2011; Wiek et al., 2014; Fraisl et al., 2020; Wehn et al., 2021). Further, the negative impacts of joint decision-making on societal actors are not implausible given the transaction costs associated with high PSC (Kirschke et al., 2024) or with participatory research (Bessert-Nettelbeck et al., 2023). Finally, the significant positive impacts of joint research decisions on politics may go back to the basic construction of the science year, asking for the influence of PSC on research policy (BMBF, 2024). This is also in line with the substantiated impact of transdisciplinary research on societal problem solving (Wiek et al., 2014; Schäfer et al., 2021). In sum, thus, the level of participation in science communication may be interwoven with additional influencing factors such as the adaptation to the respective needs of priority groups or transaction costs.

Taken together, the results of the quantitative and qualitative assessments of PSC activities and their impact reflect diverse perspectives on the role of participation as identified in various fields of research. First, there is no one-fits-all model of participation but a conglomerate of diverse interactions, demonstrating low to high levels of participation as we can find in various fields of science communication and public engagement (e.g., Wellcome Trust, 2011; Trench, 2008; Metcalfe, 2019, 2022). Second, this diversity may, but does not necessarily have to come along with a diversity of potential impacts on different priority groups, hinting at the actual design of participation which has long been discussed in the participation literature (Bryson et al., 2013; Kirschke et al., 2023). This has also been substantiated by the interviewees, highlighting various potential barriers to implementing highly effective PSC formats, including well-known barriers such as organizational difficulties or reaching relevant groups up to specific barriers to this set of projects that had been implemented during the Coronavirus pandemic.

At the same time, the results of this analysis are subject to uncertainties and limitations, which require additional analyses. First, impacts are hard to measure and subject to the attribution problems of participatory interventions (Ziegler et al., 2021; Kny et al., 2023; Volk and Schäfer, 2024). This was also emphasized by the interviewees as the qualitative analysis of the data has shown. Further, the interviewees' assessments of impacts may be subject to biases as the interviewees may feel pressure to demonstrate positive results of participation given the specific focus of the science year 'Participate'. Third, while substantial qualitative information on example activities and impacts could be included in this study in a systematized manner, no specific descriptions of projects and citations from the interviews could be included in this study due to the rather large number of cases (20) and the assured anonymity of results. While specific descriptions would have been beneficial to further explicate these examples, synthetizing these example activities and impacts still provide a major benefit of this study in addition to numerical assessments of levels of interactions and impacts only. Fourth, the sample size of the quantitative analysis is certainly limited, but the statistical methods, and notably testing procedures, were rigorously applied to avoid over- and/or misinterpretation. Hence, we think that the quantitative analysis gives some empirical evidence on the diverse perspectives on participation discussed. We hope that the results of our study provide motivation to apply the conceptual and methodological approach to other and extended data sets. Fifth, while merging quantitative and qualitative perspectives on impacts ('more' and 'better' impacts) allows us to explore the overall impact judgements of science communicators, it does not allow us to test positive and negative quantitative and qualitative impacts. Future research should account for these challenges by applying more clear-cut operationalizations of impact and focusing on tangible impacts closely related to the projects themselves, such as the measurements of direct impacts of participatory formats on knowledge and attitudes using pre−/post designs. For instance, measuring four competing hypotheses, including two positive and two negative hypotheses on quantitative and qualitative effects of science communication may further specify the exact benefits and risks of science communication.

Finally, the literature guiding this research has revealed that the PSC concept cannot easily be differentiated from related fields such as participatory research including citizen science or transdisciplinary research. Gantenberg et al. (2024), for instance, understand citizen science as a form of PSC which is, however, traditionally understood as a field of participatory research. The power shift associated with PSC such as co-decision-making in the Science Year 'Participate' is traditionally understood as participatory research, and transdisciplinarity research, more particularly (Lang et al., 2012). To account for these overlaps, future research in these different participatory fields should put more emphasis into the unique, delineating features of these concepts. This will also strengthen future studies on the comparative effects of participatory approaches in the different fields of communication, research, and governance.

6 Conclusion

The impacts of PSC have been subject to controversial discussions, yet empirical evidence on the science communicators´ perceptions of potential impacts was lacking. Based on a systematic comparison of 20 participatory science communication projects, we do not find any ideal-type PSC project but mixtures of low to high levels of participation. We also rarely find clear positive or negative impacts of these PSC levels on science, society, and politics. While the results are subject to uncertainty, they raise the question of whether the impact of participation in research is overestimated, both in terms of negative and positive impacts. The specific positive and negative impacts identified in our study further support this conclusion, hinting at the importance of different impact mechanisms in different groups. Comparative research including a systematic comparison of perspectives of different participatory fields and practices in participation-related sciences is needed to better understand the specific impact mechanisms of different fields of practice. Additional research including larger, cross-country datasets is further needed to clarify the actual impacts of participation in various contexts.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided written informed consent to participate in this study.

Author contributions

SK: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. JG: Investigation, Writing – review & editing. DK: Formal analysis, Methodology, Writing – review & editing.

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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.2025.1566429/full#supplementary-material

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