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3D Printing as an element of teaching—perceptions and perspectives of teachers at German schools

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Digital technologies that are very close to the teacher's analog field of activity, such as digital presentation, are increasingly taking place in the classroom, while digital, innovative technologies (e.g., 3D Printing) lacking such equivalents are used much less. Although such technologies are associated with more intense methodological and didactic changes, little is known about the extent to which 3D Printing is being used in German schools and how it is changing teaching and perspectives, which complicates the design of education and training measures. The use of such innovative technologies in the classroom is decisively influenced by the openness and acceptance of the teacher toward student-centered forms of learning and these technologies. The aim of the present study was to find out what expectations teachers (already) have about the use and potential of 3D Printing in the classroom and to what extent these are related to personal and/or external factors (e.g., 3D printers available in the school, number of STEM subjects). Therefore, an online-based questionnaire study was conducted with teachers in Germany ($N = 100$) who had different experiences with 3D Printing. The evaluation is based on descriptive, inferential and correlative analyses. Almost half of the teachers are equipped with 3D printers in their schools, while their use is even less widespread. In the perceptions of 3D Printing in the classroom from a methodological and didactic perspective, among other things, differences were revealed between teachers with different expertise in the knowledge and use of 3D Printing. In particular, the use of 3D Printing technology in their own lessons leads to a broader conception, especially with regard to the promotion of competencies. The results suggest theoretical models describing how to integrate 3D Printing into the classroom and concepts for 3D Printing trainings.

KEYWORDS

3D Printing, perceptions, STEM teacher, innovative technologies, teacher training

1. Introduction

How innovative is 3D Printing technology? A question that leads to different or differentiated answers depending on the perspective or area of application. In industry, 3D Printing technology is already present in many areas. Here, some have been and will continue to be more driven by developments in this technology than others. The branches of nutrition/food and fashion, as well as healthcare and aerospace, stand out in the application and research of new processes (Isi and Gurley, 2023). The latter are closely linked to areas of research in medicine. In particular, 3D Printing technology is a proven and established tool in medicine (Kalaskar, 2022) as well as in related areas of the life sciences. For example, biomedical materials that play an important role in organ transplantation, among others, are shaped using 3D Printing technology (Yan et al., 2018). 3D bioprinting is a promising approach for the production of complex biological constructs in biomedicine (Munaz et al., 2016). Another application example is 3D-printed biocarriers that help improve the efficiency of wastewater treatment (Sfetsas et al., 2021). There are many other examples of the use of 3D Printing technology in both scientific research and in industry. In line with ongoing technological developments, the use of 3D Printing technology still faces many challenges, especially in biology and medicine (e.g., in the development of printable materials, Zhou et al., 2020). In this respect, the potential of this technology is still unexploited even in the scientific field, despite its wide range of applications. For the related field of vocational education, it is obvious to include 3D Printing technology as a learning content and as a teaching-learning tool. In medical education, the use of 3D printed models in teaching human anatomy is well known, as are the associated effectiveness studies (Ye et al., 2020; Barreto et al., 2022; Ye et al., 2023). Acceptance of incorporating this technology into education is also high among students, while student knowledge of the use of 3D Printing technology for medical applications is very low (Wilk et al., 2020). Even with the innovation of 3D Printing technology in the medical and biological application field, there is a discrepancy in the integration of this technology in education. This also applies to school education, where not only content on the application of 3D Printing technology in the relevant subjects, but also the use of 3D Printing as a learning tool in the classroom appears to be less pronounced. There is a lack of well-founded data on this, both from a country-specific (e.g., Aslan and Celik, 2020) and an international perspective. In contrast to the continuously growing number of conceptual papers on the integration of 3D printers (e.g., Augusto et al., 2016; Monkovic et al., 2022; Oss Boll et al., 2023), the existing research on the use of 3D Printing technology in formal and informal education (e.g., Ford and Minshall, 2019) and the studies on the learning effectiveness of 3D Printing (e.g., Novak et al., 2021), it is only possible to make very limited statements about the actual use of this technology in the classroom and about teachers' ideas and attitudes toward its use. However, teachers' beliefs about technology have been identified as a key factor in the successful implementation of new or innovative technologies in the classroom (Sugar et al., 2004; Hew and Brush, 2007). With previous presentation and/or training on 3D Printing technology, teachers' attitudes toward the technology are preferentially positive, i.e., they would use the technology in their own classrooms; they address possible positive effects of using 3D technology in learning environments and/or recognize the potential of integrating this technology to transform open learning structures (Schelly et al., 2015; Yıldırım, 2018). The present study is based on teachers' perceptions of 3D Printing and its methodological and content-related integration into their subject teaching in lessons, but without any prior influence on these perceptions. The aim of this study is to gain insight into and describe the initial situation of teachers with regard to the integration of 3D Printing technology in the classroom, in order to derive recommendations for university teacher training and in-service training, as well as research opportunities. There is no comparable study for Germany, and the current status of the use of 3D Printing in German schools can only be inferred from published practical examples (e.g., Renner and Griesbeck, 2020; Bonorden and Papenbrock, 2022).

1.1. Outcomes of 3D Printing in education

From the perspective of 3D Printing experts, the integration of 3D Printing into teaching concepts requires competencies in the teacher and user especially in the area of 3D modeling and problem-solving competencies, creativity, and the knowledge of manufacturing and 3D Printing materials (Assante et al., 2020). Teachers who use 3D Printing technology in their classrooms also cite 3D modeling as an essential competence that students learn when participating in 3D projects, closely followed by the fostering of creative thinking and problem-solving skills, as well as technology skills (Trust and Maloy, 2017). According to the multiple competencies addressed, the active use of 3D Printing technology by students is very demanding in application of skills to implement a creative thinking and construction process—starting from an idea/problem, through modeling a solution, to printing a 3D object. With this technological complexity, the subject-based curricular learning as a result of the design/making process or in the use of the 3D objects does not take a back seat. Rather, a technology-based linking of science, technology, engineering, and mathematics (STEM) enables teaching and learning with 3D Printing in multidisciplinary, situated, subject-specific learning contexts (Pearson and Dubé, 2022). 3D Printing technology in school education is particularly closely associated with the promotion of STEM education (Ford and Minshall, 2019). In science, for example, this technology enables the understanding of complex systems, interactions and/or structures (e.g., in cell biology: Bagley and Galpin, 2015; e.g., in ecology: Kwon et al., 2020; e.g., in chemistry: Pernaa and Wiedmer, 2020); in mathematics, e.g., development of spatial visualization skills (Medina Herrera et al., 2019); in engineering, it is practical skills in the creation process (Chen and Cheng, 2021); and in engineering education, e.g., an engagement with sustainability and 3D Printing (To et al., 2023). While the expectations for 3D Printing technology are comparatively high, the research field for effective integration of 3D Printing technology into the curriculum is still very limited (Chen et al., 2023). Regardless of the discipline investigating the impact of 3D Printing technology on student learning, the learning potential of this technology is evident in STEM education as well as for non-STEM disciplines (Novak et al., 2021). In addition to creativity (e.g., Chien and Chu, 2018), spatial imagination (e.g., Wang et al., 2021), technical skills (e.g., Kwon, 2017), problem-solving skills and their linkage to creative thinking processes (e.g., Bicer et al., 2017), and cross- and interdisciplinary knowledge (Novak et al., 2021), communication and collaboration skills (especially in teaching visually impaired learners: e.g., Pantazis and Priavolou, 2017), motivation in learning (Kwon, 2017), and self-regulatory learning are also fostered in the implementation of 3D Printing projects. The latter is essentially accompanied by a mostly constructivist and hands-on as well as critically reflective and situated methodology in teaching and learning with 3D Printing (Pearson and Dubé, 2022). 3D Printing therefore has potential from both a methodological and a didactic point of view, and it is important to gain a fairly accurate insight into teachers' beliefs in these areas.

1.2. Integration 3D Printing in teaching

The 3D printer as a tool for printing prototypes and for the 3-dimensional visualization of ideas has experienced a strong boost in its integration into teaching as a result of the maker movement. Digital technologies and additive manufacturing processes, such as those used in 3D Printing, are characteristic of a wide range of making projects (Martin, 2015). Consequently, learning with 3D printers is closely related to maker-centered learning, which engages students in creative design processes in STEM disciplines (Hsu et al., 2017). Although the main goal in making is to produce a "product" that can be used, interacted with, or demonstrated (Martin, 2015), the process of designing, building, and producing is equally central to the active and problem-based learning emphasized by the maker movement (Martinez and Stager, 2013). A methodical integration of 3D Printing technology addresses both perspectives. On the one hand, it integrates the 3D object as a learning medium, i.e., it is available to teachers as a presentation medium and to learners for knowledge acquisition (Chen et al., 2023). In the learning process, the 3D printed object can be used as a subject-specific model, tool, spare part, visual/structural model or functional model, depending on the intended learning function and didactic-methodological integration (Meier et al., 2022). On the other hand, learners can be enabled to design and produce their own 3D printed objects. The design and production process spans between the 3D printer as a device and tool of the subject sciences and the 3D object as a product (e.g., the material model of an original; Meier et al., 2022). Embedded in a subject-specific context, learners go through a technology-supported model-building process when designing and printing: starting with the original, via an idea and a mental model, to the virtual model and the context-related application of a printed 3D object (with a biology example: Meier and Thyssen, 2021). If (also) the design process up to printing comes more into focus, this requires not only technological competencies on the part of the teachers, but also a (partial) "opening" of the traditional, teacher-centered teaching structures. In the synopsis of studies on learning by means of 3D Printing technology, problem- and project-based learning are mentioned as teaching concepts (Novak et al., 2021), as well as a constructivist and design/making-oriented understanding of learning (e.g., design thinking: Greenhalgh, 2016). While a problem-based learning approach is not necessarily linked to the production of 3D printed objects by learners, it can guide engagement with a subject content when combined with project-based learning. Project-based learning with integrated 3D Printing technology, on the other hand, is directly linked to learner engagement in the creative, communicative, and iterative process of producing a 3D printed object (Novak et al., 2021). Together with the integration of problem-based learning, among other things, this creates opportunities for inquiry-based learning in which learners solve real-world problems that span multiple disciplines (Ali et al., 2019). What stands out in the design process is the active (co-)design participation of the students. On the part of the teachers, this makes it necessary to plan and create various, individually adapted support activities/strategies. These include not only facilitating the use of technology, but also supporting collaboration and communication, design, and the understanding of the subject matter (Chen et al., 2023). Against this background, it is essential to know the teachers' perspective on the possible methodological and didactic integration of 3D Printing and their assessment of the possibilities of developing students' competencies in the above-mentioned areas, which requires appropriate data collection and analysis.

2. Research questions and hypothesis

Technical equipment often plays a central role or is a major obstacle for teachers when dealing with the integration of digital technology in subject lessons (in addition to a lack of competence and confidence; Bingimlas, 2009). Without access to the technology, an examination of it seems obsolete—a circumstance that does not apply equally to every technological approach. 3D Printing can also be a tool in the learning process without the physical device, for example by emphasizing 3D modeling and/or outsourcing printing to external service providers (Kantaros et al., 2022). However, assuming that an available device triggers and influences teachers' planning and thinking processes for teaching with 3D Printing, its occurrence in schools would be a first starting point for further studies or training. For Germany, there is a lack of knowledge regarding the country-specific expression of this initial technological condition as well as the associated interest in the use of 3D Printing and further training. Therefore, this study exploratively addresses the following research questions:

> *Q1a*: To what extent is 3D Printing technology a part of the digital equipment in schools, and is its use by teachers a widespread practice in German schools?
>
> *Q1b*: How is teacher interest in 3D Printing measured in terms of a desire for 3D Printing equipment in their own school and the willingness or rather participation in educational training?

A number of literature reviews have described the learning effects associated with the use of 3D Printing (see section 1.1). Increased motivation and creativity toward the 3D object and the design process (e.g., Bécar et al., 2017) as well as the promotion of subject-specific competences through the integration of 3D Printing in the classroom are examples of (presumed) effects (Ford and Minshall, 2019). However, the question remains open as to what potential teachers see in the use of 3D Printing and how their perceptions in this area are influenced by individual parameters. The following research question and hypotheses are posed:

> *Q2*: Are there differences in teachers' perceptions of the benefits of 3D Printing for student competence development according to their age (1), the subjects they teach (2) and/or 3D Printing experience/expertise (3)?
>
> *H2.1*: *Younger teachers do not differ from older teachers in their perceptions of the competencies that 3D Printing fosters in students.* [In line with the lack of empirical evidence on the relationship between age and, for example, perceptions of information and communications technology (ICT) related competencies (e.g., Guo et al., 2008)].
>
> *H2.2*: *Teachers who teach at least one or more STEM subjects differ from teachers who do not teach STEM subjects in their perceptions of the competencies that 3D Printing fosters in students*

(Corresponding to the different use of subject-specific digital media by teachers who teach a STEM subject and those who do not (Lorenz and Eickelmann, 2022), the technology for 3D Printing is also based on a subject-specific STEM orientation, which may lead to differences in teachers' perceptions of competence).

H2.3: *Teachers with more experience/expertise with 3D Printing in an educational context differ in their perceptions of the competencies that 3D Printing fosters in students* (According to Trust and Maloy (2017), in the present study these are particularly creativity, problem solving, and technological literacy).

With the integration of 3D Printing into teaching, the design process up to printing, the printed object or even the printer itself becomes the focus of the subject-related learning process (e.g., Pearson and Dubé, 2022; see section 1.2). The extent to which these integration/learning scenarios for 3D Printing are known or perceived by teachers, and the possibilities they see in the methodological and didactic design, can only be guessed at. The empirical field is based on subject-specific studies in which teachers are explicitly exposed to 3D Printing technology before they are asked to execute their ideas or own teaching scenarios for integrating 3D Printing (e.g., Trust and Maloy, 2017; Novak and Wisdom, 2020). For our study, the teachers' perceptions, without the influence of a 3D-supported learning environment or in-service training, are explored descriptively investigated with the following research question:

Q3: What are teachers' perceptions of the possibilities of integrating 3D Printing into the classroom from a didactic and/or methodological perspective?

3. Materials and methods

3.1. Instrument and data collection

Data collection was online-based and anonymous using questionnaires in 2022. The surveys were sent to and distributed at schools preferably located in the local area of the researchers in Germany. The schools contacted were randomly and equally selected with respect to a presumed inventory of 3D printers, derived from the respective information on the school's homepage. The aim was to generate a heterogeneous sample in terms of 3D Printing expertise, age and subject (see section 3.2). In this respect, there were no restrictions on participation in the survey.

The first block of the questionnaire for socio-demographic data (e.g., gender, age, school type, professional duration) is followed by eight sections of questions directly related to 3D Printing technology, with a total of 50 items (Table 1). The item format consists of content-based choice responses (single-choice or multiple-choice) as well as open and closed formats, the latter with an 8-point Likert scale (for interest: from 1 = no interest to 8 = very high interest, for consent: from 1 = strongly disagree to 8 = strongly agree, for knowledge: from 1 = not at all expressed to 8 = very highly expressed) and the option for no answer. On the one hand, the development of the questionnaire was theoretically and empirically driven, especially with regard to the items on competence promotion (see section 1.1) and didactic-methodological integration (see section 1.2). Several competency domains promoted by 3D Printing were derived from empirical studies/results for the survey, such as creativity, conceptual understanding, problem solving, and motivation [e.g., Chen and Cheng, 2021; (D) in Table 1]. The items on the methodological-didactic integration of 3D Printing in the classroom [(E)–(G) in Table 1] are based on the theoretical multidimensional concept of Meier et al. (2022) as well as empirical studies in this area (e.g., Novak et al., 2021). The integration of a questionnaire block on workshop participation and expectations for further education on 3D Printing ties in with a need that is not met or should receive more attention in the German as well as international field (e.g., Choi and Kim, 2018; Diepolder et al., 2021; (C) in Table 1). In addition to the theoretical connection, the construction of the questionnaire was based on the exchange and consensus of a multidisciplinary working group consisting of researchers with expertise in 3D Printing from four German universities and three scientific disciplines (Biology, Chemistry, and Physics). This group created an item pool from items related to the mentioned fields and feedback from teachers in the field. By selecting items, a questionnaire was created, adapted, and finalized with appropriate items in several cycles.

The question sections formed are generally not oriented to a strict direction in terms of content. The items on possible competence development and on the general perception of 3D Printing are intended to cover a wide field in order to be able to record different perceptions. Consequently, these do not form a unidimensional scale and no reliability analysis is performed. An evaluation is then done at the level of the individual item. In contrast, for the three specific areas of integration of 3D Printing technology (methodology, didactics, sustainable development) in teaching, both the individual items and their composition in a corresponding scale are analyzed. In the total sample (excluding missing statements), the scales consistently show satisfactory to good reliability, with a Cronbach's $\alpha > 0.70$ (Bühner, 2011): methodical integration of 3D Printing: $\alpha = 0.775$, $N = 93$; didactic integration of 3D Printing: $\alpha = 0.839$, $N = 82$; promoting sustainable development (SD): $\alpha = 0.907$, $N = 63$.

3.2. Sample

In total, 100 teachers (51% female, 47% male, 2% not specified) were asked about their opinions and perceptions of 3D Printing in the classroom as well as the status of digital equipment for 3D Printing at their respective schools (see section 3.2). The mean age of the participants is 44.3 years ($SD = 9.78$). The mean number of years of professional experience in the total sample is 12.48 years ($SD = 9.07$). Twenty seven teachers (27%) are employed at secondary schools ("Haupt-/Sekundarschule"), 35 teachers (35%) work at comprehensive schools ("Gesamtschule"), 32 teachers (32%) are employed at grammar schools ("Gymnasium") and 5 teachers work at other types of school (e.g., vocational school). According to the research questions (Q2) and hypotheses (H2.1–H2.3), the total group of teachers surveyed in this study was divided into subgroups.

3.2.1. Forming age groups (H2.1)

Three groups were created based on age: up to and including 40 years ($n = 34$, 31.2%), 41 to 50 years ($n = 36$, 33.0%), over 50 years ($n = 29$,

TABLE 1 Structure and design of the questionnaire.

Question section	Item count	Example items	Response format
(A) Expertise	4	My technological knowledge is…	Knowledge scale
		My informatics knowledge is…	
		My 3D Printing knowledge is …	
		Have you used a 3D printer yourself? (No/Yes, private!/Yes, for lesson planning!/Yes, in lesson!)	Multiple choice
(B) Equipment	3	Are there 3D printers at your school? (No/Yes, one!/Yes, several!/I do not know!)	Multiple choice
		Would you like to see a 3D printer purchased at your school? (No/Yes/Maybe/I cannot judge.)	Multiple choice
(C) In-service training	3	Assess your interest in attending a training seminar on the use of 3D Printing in the classroom.	Interest scale
		For training seminars on the use of 3D Printing in the classroom, here's what I'd like to see…	Open
(D) Competence promotion	10	*The following competencies can be particularly promoted in learners with the use of 3D Printing in the classroom:* e.g., creativity, model competence, problem solving competence	Consent scale
(E) General about 3D Printing	9	*When I hear the "3D Printing" term, I think…*	Consent scale
		…to the physical device.	
		…to the printed product.	
		…to the design process that can be integrated.	
		…rather to a field for other subjects.	
	9	*When thinking about 3D Printing, I see possibilities…"* e.g.,	Consent scale
		The methodical integration into the classroom.	
		The content/didactic integration into the classroom.	
		The creation of individualized/ differentiated approaches to learning	
		With 3D Printing for and in the classroom, I associate…	Open
(F) Methodical integration of 3D Printing	3	*When thinking about 3D Printing, I see opportunities for methodological integration…*	Consent scale
		Production of 3D models and 3D objects.	
		Production of experimental material.	
		To involve students in activities related to 3D Printing.	
(G) Content-related/didactic integration of 3D Printing	4	*When thinking about 3D Printing, I see possibilities for contextual and therefore didactic integration…*	Consent scale
		Technology in the disciplines corresponding to the subjects I teach.	
		Everyday context.	
		Context of societal changes and challenges.	
		Sustainability context.	
(H) Promoting sustainable development (SD)	5	*In thinking about 3D Printing, I see opportunities to promote sustainable development, through…*	Consent scale
		Production on site.	
		Printing of individual spare parts.	
		Production of parts for upcycling constructions.	
		Recycling of plastics for printing polymers.	
		SD concepts on 3D Printing.	

26.6%). Based on an assumed average age of 28 to 30 years at the beginning of the teaching profession (after completion of the practical phase and 2nd state examination), the interval size is at least 10 years.

3.2.2. Forming subject groups

Additionally, based on the data describing the subjects taught by each in-service teacher, three groups were created: no STEM subject

($n = 23$), one STEM subject ($n = 38$) and at least two STEM subjects ($n = 39$).

3.2.3. Forming experience levels (H2.3)

Furthermore, teachers were divided into groups according to their self-reported technological, informational and 3D Printing knowledge [see (A) in Table 1]. Teachers with data above the mean of the 3D Printing knowledge scale (M = 4.5) formed the 3D Printing Expert group, and teachers with data below the mean formed the 3D Printing Novice group (Table 2). Based on the self-reported knowledge, the subgroups will always be referred to as 3D Printing Experts and 3D Printing Novice in the further course of the article. To examine correlations of 3D Printing expertise, experience with 3D Printing in the classroom was used as a grouping variable in addition to self-reported knowledge in this area. All teachers who reported having used a 3D printer in their own classrooms (3D Users: $n = 22$) were compared with other teachers who had no classroom experience with 3D Printing (3D Non-Users: $n = 78$). Throughout the rest of the article, these will be referred to as 3D User and 3D Non-User. When comparing the size of the resulting groups for the three different knowledge domains (Table 2) the data indicates that the fraction of Novices is increasing from Technology via Computer Science to 3D Printing. As a result, the amount of knowledge and the number of contact persons for 3D Printing in the teaching staff is the lowest. Novices in 3D Printing also have the lowest level of knowledge. There are positive correlations (Spearman-Rho) between the three types of knowledge with strong effects in all cases (r_s between 0.652 and 0.711, all $p < 0.001$). For example, low levels of technology knowledge are associated with low levels of 3D Printing knowledge. Based on self-reported knowledge and usage there are significant differences between all three knowledge domains in both 3D Printing expertise subsamples, namely Users/Non-Users and Experts/Novices. When comparing 3D Users with 3D Non-Users the groups differ significantly (Technology Knowledge with U = 373.5, $z = -4.08$, $r = 0.41$; Computer Science Knowledge with U = 346.5, $z = -4.30$, $r = 0.43$; 3D Printing Knowledge with U = 36.5, $z = -7.19$, $r = 0.71$, all $p < 0.001$). In this respect, the 3D Non-Users consistently rate their skills lower than the 3D Users. The same ist true for the 3D Printing Novices and 3D Printing Experts (Technology knowledge with U = 282.0 $z = -5.53$, $r = 0.55$; Computer Science Knowledge with U = 271.0, $z = -5.61$, $r = 0.56$; 3D Printing Knowledge with U = 0 (due to group definition), $z = -8.05$, $r = 0.81$, all $p < 0.001$).

3.2.4. Knowledge and subjects (H2.2 & H2.3)

In addition, there are significant differences in the knowledge groups (Table 2) according to the number of STEM subjects they taught. The group with teachers who teach two STEM subjects rate their knowledge in all three areas significantly higher than teachers in the other two groups [Technology: H(2) = 16.77, $p < 0.001$; Computer Science: H(2) = 16.10, $p < 0.001$; 3D Printing: H(2) = 17.03, $p < 0.001$]. *Post hoc* Tests (Dunn-Bonferroni-Tests) show significant differences to both groups with moderate effects (Technology: 2 STEM vs. no STEM $z = -3.66$, $p < 0.001$, $r = 0.47$ and vs.1 STEM $z = -3.22$, $p = 0.001$, $r = 0.37$; Computer Sciences: 2 STEM vs. no STEM $z = -3.60$, $p < 0.001$, $r = 0.46$ and vs.1 STEM $z = -3.14$, $p = 0.002$, $r = 0.36$; 3D Printing: vs. no STEM $z = -3.63$, $r = 0.46$ and vs.1 STEM $z = -3.33$, $r = 0.38$ for both $p < 0.001$).

There are no significant differences between the three age groups in self-reported knowledge of technology, computing and 3D Printing.

3.3. Data analysis

Descriptive analyses are used to quantitatively describe the baseline situation in terms of 3D Printing equipment and teachers' perceptions. Frequencies and location and dispersion parameters [median (Mdn), mean (M), and standard deviation (SD)] will be reported. Inferential statistical procedures are used to test for group differences and correlations. Since almost all data were not normally distributed (Shapiro-Wilks and Kolmogorov–Smirnov tests, $p < 0.05$), non-parametric procedures were used to compare groups. Depending on the number of independent groups, e.g., 3D Users vs. 3D Non-Users, the Mann–Whitney *U*-test or, in the case of more than three independent groups, the Kruskal-Wallis test was used. *Post-hoc* tests (Dunn-Bonferroni test) are used to specify group differences. In this case, the adjusted value of *p* is quoted. The Wilcoxon test is used to analyze differences in the overall sample, e.g., for comparing the different perceptions of the didactic and methodological integration of 3D Printing. Spearman rank correlation (r_s) was used to test correlations. Significance level was set to $p \leq 0.05$. The effect sizes are evaluated according to Cohen (1992).

4. Results

4.1. Availability and usage of 3D Printing (Q1a)

Regarding the availability of 3D printers [see (B) in Table 1], a disproportion between the types of schools can be observed. Teachers at grammar schools ("Gymnasium": 66%) and comprehensive schools ("Gesamtschule": 54%) in particular indicate that they have one or more printers. Only one secondary school ("Haupt-/Sekundarschule") teacher states that there are 3D printers at the school. Relative to the

TABLE 2 Expert and novice subgroups related to technological, informational and 3D Printing knowledge.

Groups	Technology knowledge			Computer science knowledge			3D Printing knowledge		
	N	*Mdn*	*M ± SD*	*N*	*Mdn*	*M ± SD*	*N*	*Mdn*	*M ± SD*
Experts in…	62	6	6.31 ± 0.985	48	6	6.15 ± 1.052	27	6	6.41 ± 1.047
Novices in…	38	3	2.97 ± 1.052	52	3	2.79 ± 0.97	73	1	1.62 ± 0.922
3D Users	22	7	6.45 ± 1.405	22	6	6.05 ± 1.588	22	6.5	6.50 ± 1.185
3D Non-Users	78	5	4.64 ± 1.851	78	4	3.94 ± 1.819	78	1	1.90 ± 1.392

total sample, 45% of the teacher's report having at least one 3D printer in school (20% of teachers report having more than one), while 49% of the teachers do not have a printer in school (the rest is unsure). Just 22% of the teachers already have used 3D Printing for teaching purposes, either in preparing lessons or during lessons itself, while 22.9% already have used 3D printers for private purposes. Less than 2% of the teachers who have already used 3D Printing for lesson related purposes aren't STEM-teachers. Just 2 teachers belonging to the 3D Printing Novice group stated that they already integrated 3D Printing into their lessons, while 20 of the 3D Printing Experts did. In terms of the presence or absence of one or more 3D printers in the schools, a significant correlation can be found with classroom use, $r = 0\ 0.527$, $p < 0.001$, $N = 100$ (with a strong effect), as well as with 3D Printing Expert/Novice knowledge, $r = 0.394$, $p < 0.001$, $N = 100$ (with a moderate effect). In particular, the 3D Printing Experts state that they have one (26%) or more 3D printers (60%) available in school. While a larger group of 3D Printing Novices do not have a 3D printer (61%), 25% say they have one and 5% say they have several 3D printers in school.

4.2. Interest for 3D printers and in-service training for 3D Printing (Q1b)

Among teachers who do not have a 3D printer in their school, 44% would like to purchase one. Of those who already have one or more 3D printers in their school, 71% would like to purchase another 3D printer. In total, 56% would like to purchase (another) 3D printer, 23% say that such a purchase might be necessary, and only 8% (25% of these teachers already have a 3D printer at school) do not want to purchase one. The 3D Printing Novices ($N = 73$, $Mdn = 2$, $M = 2.62$, $SD = 0.91$) would rather appreciate a purchase than the 3D Printing Experts ($N = 27$, $Mdn = 2$, $M = 2.04$, $SD = 0.52$), $U = 613.5$; $z = -3.175$, $p < 0.001$, $r = 0.32$.

Only 14% of the teachers (based on responses from 100 respondents) have participated in 3D Printing in-service trainings [see (C) in Table 1]. The reasons given by the remaining teachers for not attending such training events were (still) a lack of interest (34%) and a lack of suitable offers (22%). Likewise, the limited time available to pursue such training plays an important role for teachers (12%). Interest in further training on 3D Printing is fairly evenly distributed among the group of respondents ($N = 74$), with 55.4% indicating no to little interest and 44.6% indicating high to very high interest. The group of 3D Printing Experts shows significantly higher interest in trainings ($Mdn = 5.5$, $M = 5.15$, $SD = 2{,}22$) than the group of 3D Printing Novices ($Mdn = 3$, $M = 3.67$, $SD = 2{,}12$) in 3D Printing ($U = 390.5$; $z = -2.676$, $p = 0.007$, $r = 0.311$). There are no differences in interest in 3D Printing education among the groups divided by age and number of STEM subjects.

4.3. Perceptions on putative competence development by 3D Printing (Q2)

For all competency areas surveyed regarding their ability to promote them with 3D Printing (see (D) in Table 1), the mean scores across all teachers were above the scale mean ($4.66 < M < 6.61$, Table 3). In the perception of the teachers, the use of 3D Printing in the classroom is mainly beneficial for the development of general technical skills and competencies in modeling. On the other hand, there is a lower value in the competence areas of communication and cooperation, which could benefit from the integration of 3D Printing in the classroom (Table 3).

4.3.1. Age and Subjects (H2.1 & H2.2)

When comparing groups of teachers of different age and number of STEM subjects, no significant differences were found between the groups in terms of their rated potential for promoting competencies. This is also the case when grouped by technological or computer science knowledge.

4.3.2. Experience levels (H2.3)

For the pairs formed with different levels of expertise, 3D Printing Novices/Experts and 3D Non-Users/Users, some differences were found in the reported scores of the competencies that can be developed through 3D Printing, with the more experienced group rating the development possibilities higher (Table 3). Based on the reported 3D Printing Knowledge significant differences can be found for promoting competencies in the areas of creativity ($U = 702.500$, $z = -2.041$, $p = 0.041$, $r = 0.21$), scientific inquiry ($U = 307.000$, $z = -3.488$, $p < 0.001$, $r = 0.41$), problem solving ($U = 358.500$, $z = -4.561$, $p < 0.001$, $r = 0.48$), and general digital competencies ($U = 670.000$, $z = -2.183$, $p = 0.029$, $r = 0.22$). The reported 3D Printing Knowledge correlates only with perceptions on fostering scientific inquiry with a medium effect ($r = 0.357$, $p = 0.002$) and problem-solving competencies ($r = 0.383$ $p < 0.001$). If the classification is based on the integration of 3D Printing into lessons, significant differences can also be found for promoting competencies in the area of creativity ($U = 554.500$, $z = -2.437$, $p = 0.015$, $r = 0.25$), scientific inquiry ($U = 286.500$, $Z = -3.293$, $p < 0.001$, $r = 0.39$), problem solving ($U = 243.000$, $z = -4.944$, $p < 0.001$, $r = 0.52$) and general digital competencies ($U = 494.000$, $z = -2.857$, $p = 0.004$, $r = 0.29$). In addition, significant differences are shown in the perception of promoting social ($U = 535.000$, $z = -2.177$, $p = 0.030$, $r = 0.22$) and communication competencies ($U = 562.000$, $z = -2.072$, $p = 0.038$, $r = 0.21$).

4.4. Perceptions about the methodical and didactical integration of 3D Printing in the classroom (Q3)

With regard to the perception of the possibilities of using 3D Printing [also with students, see (E) in Table 1], the methodological integration for the production of 3D models and objects ($Mdn = 7$, $M = 6.75$, $SD = 1.77$) is at the top of the list, while the perspective of using it as a teacher for lesson planning without involving students, for example, plays a lesser role ($Mdn = 2$, $M = 3.00$, $SD = 2.02$). When asked for a general assessment with a single item, teachers were very similar in their perceptions of the potential for integrating 3D Printing methodologically ($Mdn = 6$, $M = 5.38$, $SD = 2.34$) and didactically ($Mdn = 6$, $M = 5.28$, $SD = 2.22$). In contrast to this finding the values obtained by using the scales for methodological integration [see (F) in Table 1: $Mdn = 6.66$, $M = 6.34$, $SD = 1.57$] and didactic integration [see (G) in Table 1: $Mdn = 4.75$, $M = 4.68$, $SD = 1.74$] differed significantly with a strong effect [Wilcoxon, $z = -7.88$,

TABLE 3 Perceptions of competency areas that 3D Printing can foster as reported by panel (total sample), 3D Printing Novice/Expert, and 3D Non-User/User (pairs of values in bold indicate significant differences).

Competency areas	Total sample				3D Printing Novice				3D Printing Experts				3D Non-User				3D User			
	Mdn	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*
Creativity	7	6.61	1.64	97	7	**6.36**	1.79	70	7	**7.26**	0.90	27	7	**6.37**	1.75	75	8	**7.41**	0.80	22
Scientific inquiry	7	6.15	1.73	72	6	**5.63**	1.78	46	8	**7.08**	1.20	26	6	**5.72**	1.78	50	8	**7.14**	1.13	22
Problem solving	7	6.23	1.77	92	6	**5.74**	1.82	65	8	**7.41**	0.84	27	6	**5.79**	1.78	70	8	**7.64**	0.58	22
Cooperation/social	5	5.05	1.96	92	5	4.86	1.96	65	5	5.52	1.93	27	5	**4.79**	1.96	70	6	**5.91**	1.74	22
Modeling	7	6.52	1.44	95	7	6.37	1.50	68	7	6.89	1.25	27	7	6.37	1.50	73	7	7.00	1.15	22
Subject knowledge	5	5.38	1.70	95	5	5.19	1.69	68	6	5.85	1.66	27	5	5.23	1.74	73	6	5.86	1.46	22
Communication	5	4.66	2.12	94	4	4.45	2.18	67	5	5.19	1.90	27	4	**4.40**	2.15	72	6	**5.50**	1.82	22
SD	5	5.10	1.96	71	5	5.00	2.05	53	6	5.39	1.69	18	5	4.95	2.01	56	6	5.67	1.68	15
General digital	6	6.27	1.44	96	6	**6.07**	1.46	69	7	**6.78**	1.28	27	6	**6.05**	1.44	74	7	**7.00**	1.20	22

$p < 0.001$, $r = 0.81$, $n = 94$]. While the values derived from the two scales increased for methodological integration, they decreased for didactic integration. When comparing 3D Printing Novices and Experts, the perspectives on methodological and didactic integration are different, regardless of which of the two indicators (scale or single item) is analyzed (Table 4).

Perceptions of methodological and didactic integration correlate significantly with each other on an individual item basis with strong effect $r = 0.881$, on a scale level only with $r = 0.675$ (all $p < 0.001$). In some options for methodological and didactic integration, the ratings of 3D Printing Experts differ significantly from those of the Novices (Table 5). Looking at the perspective on a 3D printer in terms of associated thoughts, there are significant differences for 2 items. For the other items, the means and medians of the ratings of what teachers think when they hear the term "3D printing" are in a range between $3 < Mdn < 8$ and $3.68 < M < 7.07$ with minima for the items different printing processes and field for other colleagues, while maxima were observed for the items physical device and printed product ($Mdn = 8$, $M = 6.69$, $SD = 1.88$ for physical device, $Mdn = 7.5$, $M = 7.07$, $SD = 1.29$ for printed product). The results for thoughts associated with the 3D design process were $Mdn = 5$, $M = 4.94$, and $SD = 2.438$.

With regard to the perception of the possibilities for integrating 3D Printing into teaching, i.e., from a methodological, didactic and/or sustainable development (SD) perspective, 3D Printing Experts rate 3D Printing significantly differently on 7 items (Table 5). For these items, the expert ratings were higher than the novice ratings, both in terms of median and mean.

When testing for groups of teachers who had or had not used 3D Printing in the classroom, in addition to the same items with significant differences specifically related to knowledge of 3D Printing, one additional item shows significant differences (Table 5B), related to the sustainable production of spare parts. In this case, 3D Printing Users rated higher. There are no differences between the expertise groups for the other 4 ways/items in which 3D Printing can be used to promote sustainable development. The scores are between $4 < Mdn < 6$ and $4.41 < M < 5.59$ for the items covering printing spare parts, upcycling constructions, recycling and SD concepts. The scoring for printing spare parts ($Mdn = 7$, $M = 6.18$, $SD = 2.074$) and printing material for experiments as an item covering methodological aspects ($Mdn = 6.5$, $M = 6.15$, $SD = 1.835$) do not differ when compared using Wilcoxon test.

4.5. Perceptions of groups teaching different numbers of STEM subjects

Data on the use of 3D printers show a tendency that higher use, particularly in the classroom, is observed when two or more STEM subjects are taught. The comparison of 3D Printing Users and Non-Users shows an identical number of users a similar distribution in the private use of 3D Printing in contrast in addition to the difference in educational use (Table 6).

Furthermore, there are clear differences in whether teachers see 3D Printing as a domain of their own or other subjects [see (G) in Table 1] when no or at least 2 STEM subjects are taught (Table 7). According to the lowest *Mdn* values teachers with 2 STEM subjects, 3D Printing is more likely to be seen in the STEM subjects. In line with this, STEM teachers are also much more likely to classify 3D

TABLE 4 Perceptions of groups with different levels 3D Printing knowledge on methodological and didactic integration of 3D Printing into the classroom.

Integration—item or scale	3D Printing Novice				3D Printing Expert				Testing statistics			
	Mdn	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*U*	*z*	*p*	*r*
Methodical—one item [see (E) in Table 1]	6	4.97	2.366	61	7	6.30	2.09	27	549.5	−2.523	0.012	0.27
Didactical—one item [see (E) in Table 1]	5	4.60	2.199	55	7	6.73	1.46	26	317.0	−4.087	<0.001	0.45
Methodical—scale [see (F) in Table 1]	6.33	6.01	1.62	71	7.33	7.19	1.02	27	488.0	−3.767	<0.001	0.38
Didactical—scale [see (G) in Table 1]	4.25	4.27	1.67	68	6.00	5.75	1.47	26	437.0	−3.783	<0.001	0.39

TABLE 5 (A) Perceptions of groups with different levels of 3D Printing Expertise (based on self-reported knowledge) on the integration of 3D Printing in the classroom for items that show significant differences only for different levels of 3D Printing knowledge but not for different levels of technology or computer science knowledge; (B) Additional items that show significant differences only for different 3D User/Non-User in class but not for different 3D Printing, technology or computer science knowledge.

PART A	3D Printing Novice				3D Printing Expert				Testing statistics			
	Mdn	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*U*	*z*	*p*	*r*
When I hear the "3D Printing" term, I think… [see (E) in Table 1]												
…from an uninformed perspective	3	3.92	2.513	60	1	2.17	1.800	23	381.5	−3.205	0.001	0.35
…to a topic for sustainability	3	3.64	2.291	70	6	5.67	2.000	27	483.0	−3.752	<0.001	0.38
When thinking about 3D Printing, I see possibilities… [see (E) in Table 1]												
…to the linkage to curricular areas (none to many).	4	3.78	2.074	64	5	5.38	1.941	26	484.0	−3.129	0.002	0.33
…to the creation of individualized/ differentiated approaches to learning.	6	4.99	2.239	67	7	6.46	1.476	26	540.0	−2.870	0.004	0.30
…to the promotion of SD.	4	3.83	2.295	58	5	5.19	2.245	26	500.0	−2.486	0.013	0.27
When thinking about 3D Printing, I see opportunities for methodological integration… [see (F) in Table 1]												
…production of 3D models and 3D objects.	7	6.53	1.839	70	8	7.35	1.413	26	586.0	−2.838	0.005	0.29
…to involve students in activities related to 3D Printing.	6	5.58	2.199	69	8	7.44	0.934	27	427.0	−4.239	<0.001	0.43
When thinking about 3D Printing, I see possibilities for contextual and therefore didactic integration… [see (G) in Table 1]												
…everyday context.	4	4.08	2.010	66	6	5.73	1.909	26	470.0	−3.397	0.001	0.35
In thinking about 3D Printing, I see opportunities to promote sustainable development, through… [see (H) in Table 1]												
…production on site.	6	5.34	2.181	65	7	6.23	2.026	26	621.0	−1.998	0.046	0.21
PART B	**3D Non-User**				**3D User**				**Testing statistics**			
In thinking about 3D Printing, I see opportunities to promote sustainable development, through… [see (H) in Table 1]												
…printing of individual spare parts.	7	5.91	2.16	69	8	7.00	1.54	22	516.5	−2.318	0.020	0.24

TABLE 6 3D Printer usage of 3D Users/Non-Users and teachers teaching different numbers of STEM subjects [see (A) in Table 1].

N	0 STEM subject	1 STEM subject	At least 2 STEM subjects	3D User	3D Non-User
	23	38	39	22	78
None	17	28	18	0	63
Private	6	8	16	15	15
For lesson planning	2	3	11	14	2
In lessons	2	5	15	22	0

TABLE 7 Perceptions of groups teaching different numbers of STEM subjects.

3D as a…	0 STEM subject				1 STEM subject				At least 2 STEM subjects				Testing statistics					
	Mdn	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*Mdn*	*M*	*SD*	*N*	*H(2)*	*p*	*GP*	*z*	*p*	*r*
…field for other subjects.	5	4.7	2.548	23	4	4.03	2.284	38	2	3.08	2.186	38	7.310	0.026	**0 vs. 2**	2.569	0.028	0.33
…corresponding science technology in their subjects.	4	4.24	2.256	21	5	5.31	2.054	36	6	5.85	1.987	34	7.324	0.026	**0 vs. 2**	−2.706	0.02	0.36
…field for SD concepts.	3	3.42	2.364	19	5	5.22	2.063	27	5	4.53	2.091	19	6.961	0.031	**0 vs. 1**	−2.638	0.025	0.39

Printing as a corresponding science technology in their subject. With regard to a connection to SD, the picture is slightly different, as significant differences can only be observed between teachers without and with a single STEM subject. The latter see a stronger linkage.

5. Discussion and conclusion

Technological innovation is making its way into education, albeit slowly but steadily. How innovative 3D Printing technology is perceived from an educational and teaching perspective has been little studied. This study aims to provide some initial insights for Germany. Of particular interest are teachers' perceptions of the 3D printer as a teaching and learning tool in terms of skills development and the methodological and didactic integration of 3D Printing technology in the classroom. A description of the current status of 3D printers in German schools and their integration into subject lessons includes on the one hand on the equipment (Q1a) and on the other hand, of course, on the users of this technology (Q1b–Q3). Teachers are the driving force behind digitalization processes and efforts in schools. Their concepts and decisions to integrate digital technologies into the planning and delivery of teaching are influenced by many factors. These include attitudes toward digital technologies, as well as pedagogical knowledge and perceptions of effective integration in teaching, and their own technological skills (Ertmer et al., 2015).

5.1. Specifications of the sample in terms of 3D Printing expertise

In order to investigate the research questions and hypotheses (section 2), a heterogeneous sample of teachers is used, with varying numbers of STEM subjects and expertise, e.g., in technology, computer science and 3D Printing knowledge. In line with the study's focus on 3D Printing technology, the expertise of the teachers surveyed in this area is included in the analyses in the form of self-reported knowledge and use of 3D Printing in their own teaching. For this purpose, groups of Experts are compared with Novices and groups of Users with Non-Users. The decisive feature and legitimation for this grouping are the significant differences that exist in the self-reported areas of knowledge and use in teaching. Here, the scores of Experts and Users are consistently higher than those of Novices and Non-Users. Drossel et al. (2017) report that self-efficacy in preparing lessons involving the use of ICT is the only significant predictor of the use of computer use in schooling that is found in all countries surveyed. Like our data, their models also show no significant role for age, but experience in using ICT was one of the factors with the highest impact. The postulated differences between the groups in the context of 3D Printing may arise from the transformative, constructivist ideas attributed to Experts for designing digitally supported instruction in which they are consultative and open to new ideas (Berg et al., 1998; Meskill et al., 2002).

5.2. Current status on 3D Printing in German schools (Q1)

The 3D printer is no longer a newcomer either, and the equipment in German schools looks promising. About half of the teachers surveyed in this study said they had one or more 3D printers in their school. While there is room for improvement, especially in the much less well-equipped secondary schools ("Gymnasien"), this already opens up some possibilities for integrating this technology. In terms of both school type and level of use, the current picture in Germany is roughly supported by findings from other countries (Choi and Kim, 2018). Assuming that equipment has increased over the years, the main difference with Korea is not in the equipment. Rather, the difference lies in the use of 3D printers in the classroom, which is about three times higher there. Although there are currently positive correlations between 3D Printing Experts, classroom use and the availability of 3D printers, for some (particularly in the 3D Printing Novice group) the 3D printer remains unused despite its availability. In a study by Drossel et al. (2017), the availability of sufficient ICT equipment was a significant factor for the integration of computers in only one of three countries. Due to the different ways in which 3D Printing can be integrated into the classroom (even outsourcing printing is possible; Kantaros et al., 2022), the availability of equipment is not necessarily an essential factor. In our study, however, there is a strong correlation between the availability of 3D printers and their integration into the classroom. Furthermore, access to 3D printers is not exceptionally low compared to data describing the accessibility of tablet sets to whole classes, which is reported at 66% for Germany (IU Internationalen Hochschule, 2022). The fact that only 22% of teachers have already integrated 3D Printing into the classroom suggests that the general availability of printers may not be the limiting factor, as 45% of teachers report having one in their school. So there have to be other factors, e.g., interest or motivational aspects.

The interest in 3D Printing is quite positive in the sample of teachers with different subjects and 3D Printing knowledge studied here, which corresponds to the "desire" to acquire 3D printers at their own school. However, the fact that around half of teachers report a high or very high level of interest in attending a training course may indicate that they feel insecure in some way. Access to technology can be one of the many barriers teachers face when planning and implementing digitally-enhanced lessons (e.g., Pelgrum, 2001). However, even if access were a prerequisite for engaging with technology, many other factors or barriers come into play that do not usually resolve themselves (Hew and Brush, 2007). Thus, the availability of 3D printers in schools does not (consistently) lead to their integration into the classroom. As the data shows, the use of 3D Printing in the private sector is already more pronounced in all STEM groups. Therefore, experience gained in this area may support integration into the classroom in the future. Both the range of instructional materials/concepts and, in particular, the range of training to build competencies and self-efficacy are at least equally important as the equipment for integrating 3D Printing into one's teaching (e.g., Arslan and Erdogan, 2021). The adoption of novel technology is largely determined by personal factors. Performance expectancy (related to advantages of 3D Printing), anxiety (of making mistakes or against 3D Printing technology), and attitudes toward technology use are significant predictors of teachers' behavioral intentions when using new technologies (Holzmann et al., 2020), as 3D Printing represents for many. Training enables teachers to first gain their own experience with the technology as learners, to reflect on its pedagogical value, to form positive attitudes and reduce fears, and then to learn as teachers how to use 3D models in the classroom (e.g., Novak et al., 2021; Chen et al., 2023). Among the teachers in our study, the completion of a training course on 3D Printing is clearly underrepresented. The reasons given for this are a lack of interest and time, as well as a lack of courses on offer. While the intrinsic motivation to participate must be provided by the teachers themselves, the findings point to necessary implications in pre-service and in-service teacher training. Especially in the regular school routine of a working teacher, a lot can be achieved with short one-day training courses on 3D Printing, especially when time is a barrier (Novak, 2019). But that is also the case for courses at universities as shown by Ishutov et al. (2021) or Thoms et al. (2022). In interpreting our data in this context, it is worth noting that the proportion of newcomers is increasing from technology through computing to 3D Printing knowledge. 3D Printing as a technology in the area of modeling and simulation is by far the area with the highest demand for or low supply of training (in Germany: Diepolder et al., 2021).

5.3. Perceptions of competence development with 3D Printing in the classroom (Q2)

The teachers in this study perceived an increase in competencies through the integration of 3D Printing, especially in the areas of creativity, modeling and technology, closely followed by problem solving and scientific inquiry. This goes hand in hand with teacher/educator and student competencies (Trust and Maloy, 2017; Assante et al., 2020), but can be further differentiated in terms of 3D Printing expertise for the present study. We found empirical support for one of our three research hypotheses. The presumed differences depending on the expert status of the teachers with regard to 3D Printing can be partially confirmed in the areas of competence development through the incorporation of 3D Printing investigated here (H2.3). Teachers with a high level of 3D Printing knowledge rate 3D Printing as a valuable tool for developing competencies in scientific inquiry, problem solving and general aspects of digitalization. For fostering competencies in scientific inquiry, problem solving there is also a high correlation with 3D Printing knowledge. Since a comparison of teachers with high and low technological and computer science knowledge does not show significant results, it seems that knowledge of 3D Printing in particular is required to gain this insight, at least in theory. Even more interesting is the fact that the experience of integrating 3D Printing into the classroom does not seem to change these assumptions related to such areas of competence development. In contrast, teachers who have already integrated 3D Printing into their teaching rate the same items significantly higher, but seem to see further potential in additional areas such as social and communication competencies. It seems that seeing students working in the field of 3D Printing enables teachers to identify potential that cannot be derived from theoretical reflection alone. This is in line with the findings of Thyssen et al. (2021), who show that willingness and plans to use ICT in the future show stronger correlations with their current use than with Technological Knowledge or Technological Pedagogical Knowledge (according to the TPACK model, Koehler et al., 2013), and even has a higher weight as a predictor in a regression model.

With regard to the three age groups and three subgroups on the number of STEM subjects formed in this study, a presumed relationship with the assessment of the development of competences with 3D Printing cannot be established (H2.1 and H2.2 must be rejected for the present sample).

5.4. Perceptions about the integration of 3D Printing in the classroom (Q3)

In addition to the external barriers, which the teacher has little control over, they themselves still face the challenge of thinking about the benefits of digital technologies and deriving potentials (possibly also 3D Printing in combination with other digital technologies, Caldarone, 2020) as well as acquiring knowledge and skills for integrating them [second-order barriers according to Ertmer (1999)]. Our data show that knowledge of 3D Printing and a differentiated, rather than general, approach seem to have an impact on the assessment of didactic and methodological aspects that are essential for considering the benefits of using 3D Printing in the classroom. Both factors led to significant differences when comparing the 3D Printing expertise groups and the way of rating, respectively. In particular, the increase in the rating of methodological integration when assessed in a more nuanced approach using a multiple item scale could indicate that practical trainings that allow experiencing real lessons and thus actual methodological implementations could have beneficial effects due to the observations that can be made. This type of peer observation is helpful in several variations (Hamilton, 2013). Furthermore, more than 50% of the items tested for methodological and/or didactic integration of 3D Printing correlate significantly with knowledge of 3D Printing. Taken together, this demonstrates the need for more training courses in which teachers can acquire the relevant knowledge and adequate perspectives on 3D Printing. It would be important to provide teachers (including pre-service teachers) with approaches for differentiated consideration, pedagogical concepts and models for integrating 3D Printing in the classroom; such as essential content of in-service training (Assante et al., 2020).

Meier et al. (2022) provide a theoretical approach that reflects priorities with respect to didactic or methodological, product or process oriented, and subject-internal aspects. Based on these three perspectives of integration in the classroom, a three-dimensional space can be created to reflect on the objectives and content of the lesson. The base is formed by two fixed axes that can represent the focus of integration in terms of didactics or methodology (axis 1 in Figure 1), and the printer itself, the printed product, or the process in between (axis 2 in Figure 1). The 3D printer as a physical device and the 3D Printing product is very present in the perceptions of the surveyed teachers in the present study. In contrast, the inclusion or the perception of the design process as a possible way to integrate 3D Printing in the classroom is more in the middle range of agreement. This could be due to the fact that most of the teaching concepts and materials available focus often on a specific 3D Printing product (e.g., Jones and Spencer, 2018; Haverkamp et al., 2021). In addition, perceptions of the 3D printed product and its use in the classroom are probably closer to the common use of media (in this case, models) in the subject lesson. In contrast, the integration of the design process for printing is linked to knowledge of the technology and the process steps and usually also leads to changes in the teaching concept.

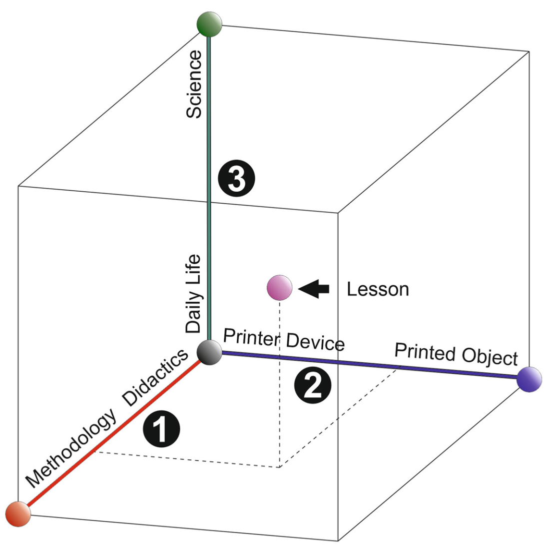

FIGURE 1
Dimensions and decision fields of the integration of 3D Printing during lesson planning, adapted from Meier et al. (2022).

Learning situations in which students digitally design models themselves and then physically print them out are not possible without partially adopting concepts from the maker movement, and are closely linked to a constructivist understanding of learning (Pearson and Dubé, 2022). In the creation of self-directed learning environments in which individual and differentiated approaches to learning are made possible, there is potential for the 3D Printing Experts in this study in learning through 3D Printing. They differed significantly from the 3D Printing Novices in their conception of this. This observation could be interpreted to mean that 3D Printing supports constructivist learning or approaches that incorporate design thinking concepts or methods based on them and elements derived from them are seen as promising by teachers. The extent to which these teachers also methodically implement design thinking supported by 3D Printing into their own classrooms can vary widely and does not necessarily need to take advantage of the full potential of 3D Printing. In fact, it may be as simple as just integrating a few elements (Leinonen et al., 2020). However, this was not explicitly addressed in the context of the study or covered with specific items and should be explored in more detail in follow-up studies.

Perpendicular to axes 1 and 2 is a third, context-dependent axis (axis 3 in Figure 1), each consisting of a pair of terms describing relevant contextual areas. The vertical axis is to be understood as a flexible set of, possibly subject-dependent axes to capture the relevant contexts. In STEM education, contexts can be represented by axes with different extremes, such as science or everyday life or for other subjects and contexts 3D Printing/design process and 3D Printing equipment technology, chemistry of 3D Printing and technology of 3D Printing process. The comparison of our data, according to which STEM teachers see a higher possibility of integrating 3D Printing as content in the sense of a corresponding science technology in their subjects, with the presented model (Figure 1, axis 3: daily life/science) allows two interesting interpretations: the model can (a) explain the differences between STEM subjects that have emerged on this topic and (b) potentially predict a larger space for the integration of 3D Printing in STEM subjects. For contextual perspective and adaptation, different pairs of terms should be formulated for the third axis depending on the subject. STEM subjects or teachers' perceptions do not seem to differ fundamentally in areas relevant to lesson planning in general. The perception of the possibilities of methodological or didactic integration and the integration of printed products or the design process do not seem to be STEM specific. This means that a model with a more or less general but adaptable structure may be appropriate and flexible enough to account for the observed differences. The needs of different subjects can be met by adjusting the third axis for analytical purposes. However, this will not change the observation that at least right now STEM subjects have the potential of integrating 3D Printing in the context of science (e.g., HU and Jiang, 2017; Walker and Humphries, 2019) matching higher assessment of an integration in SD concepts while teachers of other subjects seem to assess reduced possibilities for both fields.

5.5. Link to the (NON-)STEM subjects taught

For self-reported knowledge in the mentioned areas (Table 2), a significant difference can be found between teachers with two STEM subjects and teachers with one or no STEM subject. One explanation for these differences may be the specificity of computer science and 3D Printing knowledge in particular, which may be associated with related technologies in science. This interpretation would be supported by the finding that teachers with two STEM subjects, when they think of 3D Printing, are less likely to think of it as a field for other subjects, and see opportunities for integration into the classroom as an established technology in scientific fields corresponding to their subjects. The use of digital technologies is less influenced by the subject in terms of scope, but is certainly influenced by the subject in terms of the design and type of technologies incorporated (e.g., Záhorec et al., 2019). However, the number of putative effects that may exist in terms of the number of STEM subjects taught is small. Apart from the actual use of 3D printers, significant effects can only be found for 6 items, three of which, as reported, concern the information on the existing knowledge, two the reference to the own teaching subjects and one the promotion of sustainability competences with corresponding SD concepts using 3D Printing. This suggests that there may also be determinants in the latter area, which are not directly linked to 3D Printing knowledge but to the number of STEM subjects compared to the differences found for stated knowledge. Similarly, the alignment between STEM and non-STEM teachers in the use of 3D Printing evidenced in other studies and countries (Chen et al., 2023) may also be evident in our study. Certainly, teachers' perceptions and perspectives will change, driven by self-taught dynamics or those specifically initiated by in-service training.

6. Implication: what can be derived from this study for future training concepts?

Teaching with 3D Printing in the classroom is now coming up against not so much equipment limitations as training limitations (Pearson and Dubé, 2022), which are narrowly defined by a (still) very small number. Following on from the reported findings on perceptions of 3D Printing in the present study, training courses for Novices and Experts need to be developed, adapted to the level of experience and knowledge as well as to the interests of the participants. Ideally, these courses should include a pedagogical approach to the use of 3D Printing in the classroom (Assante et al., 2020) and practical approaches in schools, rather than focusing solely on technical aspects. As it is clear that the use of 3D Printing in the classroom provides additional insights and perceptions in terms of fostering interaction and communication skills, new training approaches could also be considered. Implementations that allow teachers to observe real lessons and experience student interaction and communication could potentially provide such perceptions directly. New or more hands-on training formats raise questions about the impact and sustainability of training in technology use.

Another targeted alternative would be further training with observation of the teaching of experts, with novices even assisting as co-teachers after their own training. Such an approach would specifically encourage peer support, which is difficult to build due to the still small number of 3D Printing users. This concept could be used to initiate a specific form of cooperation between teachers, the Professional Learning Communities (PLC). In PLCs, ideally, practitioners ("teachers as learners"; Bonsen and Rolff, 2006, p. 169) work together continuously, cooperatively and critically by exchanging ideas about their own teaching and subject content. It is assumed that teachers' collaboration can support their professional development (e.g., Terhart and Klieme, 2006; Methlagl, 2022). The assumed positive relationship between teacher collaboration and teacher competence is derived from situated learning approaches (Putnam and Borko, 2000; Borko, 2004). Learning to teach in applied situations/contexts supports the transfer of "new learning" into one's own or future teaching.

7. Limitations and further research

Limiting factors for the validity of the findings in this study include the sample generation. With regard to the equipment with 3D printers and their use, the sample may be biased as several teachers from a school may have responded to the survey and it is unclear how many teachers were actually in the same school. However, the specification of the school could have had an unfavorable effect on the feeling of anonymity during participation and consequently lead to lower participation. As a result, the respondents were not asked to name their own school.

With the intention of broadly capturing and describing the teachers' perceptions, a questionnaire with content-rich items and different item formats was developed. This has a limiting effect on the evaluation procedures and the nature of the results. Models that explain the relationships and interactions of factors in an explanatory way cannot be derived from the data collected for a descriptive survey, as there are no scales for variables that (could) interact in model contexts. This is where future research is needed to develop appropriate scales (e.g., Gürer et al., 2019) to fit new or existing models on the basis of available data. In addition, qualitative methods should be increasingly included in the collection and analysis of attitudes and perceptions about 3D Printing. This is already more common in intervention or evaluation studies (e.g., Song, 2018), but could be expanded with an eye toward teachers' general and subject-specific conceptions of 3D Printing. This will also require comprehensive statistical surveys of 3D Printing, equipment, and existing training to validate our findings. In this context, an analysis of existing training concepts would be particularly helpful for the development of new training courses (e.g., Novak and Wisdom, 2020; Cuun, 2021).

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 patients/participants provided their written informed consent to participate in this study.

Author contributions

CT and MM analyzed, revised, and discussed the data. All authors contributed to the article and approved the submitted version.

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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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References

Ali, N., Khine, M. S., Wisdom, S., and Novak, E. (2019). "Using 3D printing to enhance STEM teaching and learning" in *Integrating 3D printing into teaching and learning. Practitioners' perspectives*. eds. N. Ali and M. S. Khine (Leiden: Brill), 187–205.

Arslan, A., and Erdogan, I. (2021). Use of 3D printers for teacher training and sample activities. *Int. J. Progress. Educ.* 17, 343–360. doi: 10.29329/ijpe.2021.346.22

Aslan, A., and Celik, Y. (2020). A literature review on 3D printing technologies in education. *Int J 3D Print Technol Digit Industry* 6, 592–613. doi: 10.46519/ij3dptdi.1137028

Assante, D., Cennamo, G. M., and Placidi, L. (2020). 3D printing in education: an European perspective. In: *IEEE Global Engineering Education Conference (EDUCON)* 1133–1138.

Augusto, I., Monteiro, D., Girard-Dias, W., dos Santos, T. O., Rosa Belmonte, S. L., Pinto de Oliveira, J., et al. (2016). Virtual reconstruction and three-dimensional printing of blood cells as a tool in cell biology education. *PLoS One* 11:e0161184. doi: 10.1371/journal.pone.0161184

Bagley, J. R., and Galpin, A. J. (2015). Three-dimensional printing of human skeletal muscle cells: An interdisciplinary approach for studying biological systems. *Biochem. Mol. Biol. Educ.* 43, 403–407. doi: 10.1002/bmb.20891

Barreto, J. E. F., Kubrusly, B. S., Lemos Filho, C. N. R., Silva, R. S., Façanha, S. d. O., Santos, J. C. C. d., et al. (2022). 3D printing as a tool in anatomy teaching. *Int J Innov Educ Res* 10, 58–71. doi: 10.31686/ijier.vol10.iss6.3771

Bécar, J. P., Vareille, J., Cayez, V., and Notteau, Y. (2017). 3D printing ist boosting the Student's creativity. In: *ICERI2017 Proceedings*, 1817–1823.

Berg, S., Ridenour Benz, C., Lasley, T. J., and Raisch, C. D. (1998). Exemplary technology use in elementary classrooms. *J. Res. Comput. Educ.* 31, 111–122. doi: 10.1080/08886504.1998.10782245

Bicer, A., Nite, S. B., Capraro, R. M., Barroso, L. R., Capraro, M. M., and Lee, Y. (2017). Moving from STEM to STEAM: the effects of informal STEM learning on students' creativity and problem solving skills with 3D printing. In: *IEEE Frontiers in Education Conference (FIE)* 1-6.

Bingimlas, K. A. (2009). Barriers to the successful integration of ICT in teaching and learning environments: a review of the literature. *Eurasia J Maths Sci Technol Educ* 5, 235–245. doi: 10.12973/ejmste/75275

Bonorden, M., and Papenbrock, J. (2022). Evidence-based optimization of classroom teaching units using 3D printers for designing models—from the 2D picture to the 3D flower model. *Educ. Sci.* 12:11. doi: 10.3390/educsci12110831

Bonsen, M., and Rolff, H.-G. (2006). Professionelle Lerngemeinschaften von Lehrerinnen und Lehrern (Professional learning communities for teachers). *Zeitschrift für Pädagogik* 52, 167–184. doi: 10.25656/01:4451

Borko, H. (2004). Professional development and teacher learning: mapping the terrain. *Educ. Res.* 33, 3–15. doi: 10.3102/0013189X033008003

Bühner, M. (2011). *Einführung in die Test- und Fragebogenkonstruktion* (3rd Edn.). München: Pearson.

Caldarone, A. (2020). Mixed reality, 3D printing, and storytelling: methodologies for the creation of multi-sensory scenarios in the field of cultural heritage. In: *Proceedings CAA*.

Chen, Y., Cao, L., and Zhang, Y. (2023). Teachers as makers: how K-12 teachers design 3D making lessons for classroom teaching. *Educ. Inf. Technol.* 28, 6947–6975. doi: 10.1007/s10639-022-11475-w

Chen, J., and Cheng, L. (2021). The influence of 3D printing on the education of primary and secondary school students. *J. Phys. Conf. Ser.* 1976:012072. doi: 10.1088/1742-6596/1976/1/012072

Chien, Y.-H., and Chu, P.-Y. (2018). The different learning outcomes of high school and college students on a 3D-printing STEAM engineering design curriculum. *Int. J. Sci. Math. Educ.* 16, 1047–1064. doi: 10.1007/s10763-017-9832-4

Choi, H., and Kim, J. M. (2018). Implications for activating 3D printer use for education in elementary and secondary schools. *Int J Adv Sci Engineer Inform Technol* 8, 1546–1551. doi: 10.18517/ijaseit.8.4-2.5722

Cohen, J. (1992). A power primer. *Psychol. Bull.* 112, 155–159. doi: 10.1037/0033-2909.112.1.155

Cuun, H. (2021). A study on the impact of 3D printing and artificial intelligence on education and learning process. *Sci. Prog.* 2021, 1–5. doi: 10.1155/2021/2247346

Diepolder, C., Weitzel, H., Huwer, J., and Lukas, S. (2021). Verfügbarkeit und Zielsetzungen digitalisierungsbezogener Lehrkräftefortbildungen für naturwissenschaftliche Lehrkräfte in Deutschland. *ZfDN* 27, 203–214. doi: 10.1007/s40573-021-00134-1

Drossel, K., Eickelmann, B., and Gerick, J. (2017). Predictors of teachers' use of ICT in school – the relevance of school characteristics, teachers' attitudes and teacher collaboration. *Educ. Inf. Technol.* 22, 551–573. doi: 10.1007/s10639-016-9476-y

Ertmer, P. A. (1999). Addressing first- and second-order barriers to change: strategies for technology integration. *Educ. Technol. Res. Dev.* 47, 47–61. doi: 10.1007/BF02299597

Ertmer, P. A., Ottenbreit-Leftwich, A. T., and Tondeur, J. (2015). Teachers' beliefs and uses of technology to support 21st-century teaching and learning. *Int. Handbook Res. Teach Beliefs* 403, 403–419.

Ford, S., and Minshall, T. (2019). Invited review article: where and how 3D printing is used in teaching and education. *Addit. Manuf.* 25, 131–150. doi: 10.1016/j.addma.2018.10.028

Greenhalgh, S. (2016). The effects of 3D printing in design thinking and design education. *J Engineer Design Technol* 14, 752–769. doi: 10.1108/JEDT-02-2014-0005

Guo, R. X., Dobson, T., and Petrina, S. (2008). Digital natives, digital immigrants: An analysis of age and Ict competency in teacher education. *J. Educ. Comput. Res.* 38, 235–254. doi: 10.2190/EC.38.3.a

Gürer, M. D., Tekinarslan, E., Kocaayak, I., and Gonultas, S. (2019). Development and validation of an attitude assessment scale for the use of 3D printing in education. *Int. J. Educ. Dev. Using Inf. Commun. Technol.* 15:204.

Hamilton, E. R. (2013). His ideas are in my head: peer-to-peer teacher observations as professional development. *Prof. Dev. Educ.* 39, 42–64. doi: 10.1080/19415257.2012.726202

Haverkamp, N., Havemann, J., Holz, C., Ubben, M., Schlummer, P., and Pusch, A. (2021). A new implementation of Kundt's tube: 3D-printed low-cost set-up using ultrasonic speakers. *Phys. Educ.* 56:025023. doi: 10.1088/1361-6552/abd0d7

Hew, K. F., and Brush, T. (2007). Integrating technology into K-12 teaching and learning: current knowledge gaps and recommendations for future research. *Educ. Technol. Res. Dev.* 55, 223–252. doi: 10.1007/s11423-006-9022-5

Holzmann, P., Schwarz, E. J., and Audretsch, D. B. (2020). Understanding the determinants of novel technology adoption among teachers: the case of 3D printing. *J. Technol. Transf.* 45, 259–275. doi: 10.1007/s10961-018-9693-1

Hsu, Y.-C., Baldwin, S., and Ching, Y.-H. (2017). Learning through making and maker education. *Tech Trends* 61, 589–594. doi: 10.1007/s11528-017-0172-6

Hu, L., and Jiang, G. (2017). 3D printing techniques in environmental science and engineering will bring new innovation. *Environ. Sci. Technol.* 51, 3597–3599. doi: 10.1021/acs.est.7b00302

Ishutov, S., Hodder, K., Chalaturnyk, R., and Zambrano-Narvaez, G. (2021). A 3D printing short course: a case study for applications in the geoscience teaching and communication for specialists and non-experts. *Front. Earth Sci.* 9:601530. doi: 10.3389/feart.2021.601530

Isi, C., and Gurley, M. (2023). 3D PrintingTrend report 2023. Market insights and forecasts in additive manufacturing. HUBS. Available at: https://www.Hubs.Com/get/trends/ (accessed 24 May 2023).

IU Internationalen Hochschule (2022). Wie digital sind unsere Schulen? Available at: https://static.iu.de/studies/Digitale_Bildung_Studie.pdf (Accessed 31 May 2023).

Jones, O. A. H., and Spencer, M. J. S. (2018). A simplified method for the 3D printing of molecular models for chemical education. *J. Chem. Educ.* 95, 88–96. doi: 10.1021/acs.jchemed.7b00533

Kalaskar, D. M. (2022). *3D printing in medicine. 2nd* Edn Sawston: Elsevier Science, Woodhead Publishing.

Kantaros, A., Diegel, O., Piromalis, D., Tsaramirsis, G., Khadidos, A. O., Khadidos, A. O., et al. (2022). 3D printing: making an innovative technology widely accessible through makerspaces and outsourced services. *Mater. Today* 49, 2712–2723. doi: 10.1016/j.matpr.2021.09.074

Koehler, M. J., Mishra, P., and Cain, W. (2013). What is technological pedagogical content knowledge (TPACK)? *J. Educ.* 193, 13–19. doi: 10.1177/002205741319300303

Kwon, H. (2017). Effects of 3D printing and design software on students' interests, motivation, mathematical and technical skills. *J STEM Educ* 18, 37–42.

Kwon, S.-H., Lee, Y.-J., and Kwon, Y.-J. (2020). An active learning approach to investigate the ecosystem of tide flats using 3D modeling and printing. *J. Biol. Educ.* 54, 88–97. doi: 10.1080/00219266.2018.1546760

Leinonen, T., Virnes, M., Hietala, I., and Brinck, J. (2020). 3D printing in the wild: adopting digital fabrication in elementary school education. *Int J Art Design Educ* 39, 600–615. doi: 10.1111/jade.12310

Lorenz, R., and Eickelmann, B. (2022). "Nutzung digitaler Medien im Unterricht der Sekundarstufe I und Nutzungsbedingungen im Trendvergleich von 2017 und 2021" in *Schule digital – der Länderindikator 2021. Lehren und Lernen mit digitalen Medien in der Sekundarstufe I in Deutschland im Bundesländervergleich und im Trend seit 2017*. eds. R. Lorenz, S. Yotyodying, B. Eickelmann and M. Endberg (Münster, New York: Waxmann), 63–88.

Martin, L. (2015). The promise of the maker movement for education. *J Pre-Coll Engineer Educ Res* 5, 30–39. doi: 10.7771/2157-9288.1099

Martinez, S. L., and Stager, G. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Torrance: Constructing Modern Knowledge Press.

Medina Herrera, L., Castro Pérez, J., and Juárez Ordóñez, S. (2019). Developing spatial mathematical skills through 3D tools: augmented reality, virtual environments and 3D printing. *Int. J. Interact. Des. Manuf.* 13, 1385–1399. doi: 10.1007/s12008-019-00595-2

Meier, M., Schubatzky, T., Obczovsky, M., Thoms, L.-J., and Thyssen, C. (2022). Fachdidaktische Perspektiven und Szenarien des 3D-Drucks im naturwissenschaftlichen Unterricht. *MNU J.* 1, 79–84.

Meier, M., and Thyssen, C. (2021). Vom Original zum 3D-Objekt. Dimensionen und Guidelines zum 3D-Druck im Unterricht. *Unterricht Biologie, Reihe BioDigital.* 463, 43–47.

Meskill, C., Mossop, J., and DiAngelo, S., nd Pasquale, R. K. (2002). Expert and novice teachers talking technology: precepts, concepts, and misconcepts. *Lang. Learn. Technol.* 6, 46–57.

Methlagl, M. (2022). Patterns of teacher collaboration, professional development and teaching practices: a multiple correspondence analysis of TALIS 2018. *Int J Educ Res Open* 3:100137. doi: 10.1016/j.ijedro.2022.100137

Monkovic, J. M., Jones, S. M., Nicolas, M., Katyal, P., Punia, K., Noland, D., et al. (2022). From concept to reality: the use and impact of 3D prints as academic tools for high school biology education. *J. Biol. Educ.* 56, 528–539. doi: 10.1080/00219266.2020.1858927

Munaz, A., Vadivelu, R. K., John, J. S., Barton, M., Kamble, H., and Nguyen, N.-T. (2016). Three-dimensional printing of biological matters. *J Sci Adv Materials Devices* 1, 1–17. doi: 10.1016/j.jsamd.2016.04.001

Novak, J. I. (2019). "Re-educating the educators: collaborative 3D printing education" in *Interdisciplinary and international perspectives on 3D printing in education*. eds. I. Santos, N. Ali and S. Areepattamannil (Hershey: IGI Global), 28–49.

Novak, E., Brannon, M., Librea-Carden, M. R., and Haas, A. L. (2021). A systematic review of empirical research on learning with 3D printing technology. *J. Comput. Assist. Learn.* 37, 1455–1478. doi: 10.1111/jcal.12585

Novak, E., and Wisdom, S. (2020). "Using 3D printing in science for elementary teachers" in *Active learning in college science: The case for evidence-based practice*. eds. J. J. Mintzes and E. M. Walter (Cham: Springer), 729–739.

Oss Boll, H., de Castro Leitão, M., Garay, A. V., Batista, A. C. C., de Resende, S. G., da Silva, L. F., et al. (2023). SynBio in 3D: the first synthetic genetic circuit as a 3D printed STEM educational resource. *Front. Educ.* 8:1110464. doi: 10.3389/feduc.2023.1110464

Pantazis, A., and Priavolou, C. (2017). 3D printing as a means of learning and communication: the 3Ducation project revisited. *Telematics Inform.* 34, 1465–1476. doi: 10.1016/j.tele.2017.06.010

Pearson, H. A., and Dubé, A. K. (2022). 3D printing as an educational technology: theoretical perspectives, learning outcomes, and recommendations for practice. *Educ. Inf. Technol.* 27, 3037–3064. doi: 10.1007/s10639-021-10733-7

Pelgrum, W. J. (2001). Obstacles to the integration of ICT in education: results from a worldwide educational assessment. *Comput. Educ.* 37, 163–178. doi: 10.1016/S0360-1315(01)00045-8

Pernaa, J., and Wiedmer, S. (2020). A systematic review of 3D printing in chemistry education – analysis of earlier research and educational use through technological pedagogical content knowledge framework. *Chem Teach Int* 2:20190005. doi: 10.1515/cti-2019-0005

Putnam, R. T., and Borko, H. (2000). What do new views of knowledge and thinking have to say about research on teacher learning? *Educ. Res.* 29, 4–15. doi: 10.3102/0013189X029001004

Renner, M., and Griesbeck, A. (2020). Think and print: 3D printing of chemical experiments. *J. Chem. Educ.* 97, 3683–3689. doi: 10.1021/acs.jchemed.0c00416

Schelly, C., Anzalone, G., Wijnen, B., and Pearce, J. M. (2015). Open-source 3-D printing technologies for education: bringing additive manufacturing to the classroom. *J Vis Lang Comput* 28, 226–237. doi: 10.1016/j.jvlc.2015.01.004

Sfetsas, T., Patsatzis, S., and Chioti, A. (2021). A review of 3D printing techniques for bio-carrier fabrication. *J. Clean. Prod.* 318:128469. doi: 10.1016/j.jclepro.2021.128469

Song, M. J. (2018). Learning to teach 3D printing in schools: how do teachers in Korea prepare to integrate 3D printing technology into classrooms? *Educ. Media Int.* 55, 183–198. doi: 10.1080/09523987.2018.1512448

Sugar, W., Crawley, F., and Fine, B. (2004). Examining teachers' decisions to adopt new technology. *Educ. Technol. Soc.* 7, 201–213.

Terhart, E., and Klieme, E. (2006). Kooperation im Lehrerberuf: Forschungsproblem und Gestaltungsaufgabe. *Zeitschrift für Pädagogik* 52, 163–166. doi: 10.25656/01:4450

Thoms, L. J., Hoyer, C., and Girwidz, R. (2022). "A teacher training course on using digital Media for Acquisition, visualization and 3D printing of complex data and for fostering pupils' experimental skills" in *Physics teacher education. Challenges in physics education*. eds. J. Borg Marks, P. Galea, S. Gatt and D. Sands (Cham: Springer)

Thyssen, C., Pankow, A., Klaeger, K., and Chernyak, D. (2021). Kompetenzen und Nutzungsperspektiven im Bereich digitaler Medien bei Lehrkräften zur Erkenntnisgewinnung in den Naturwissenschaften. *Zeitschrift Empirische Pädagogik* 35, 112–135.

To, T. T., Al Mahmud, A., and Ranscombe, C. (2023). Teaching sustainability using 3D printing in engineering education: An observational study. *Sustainability* 15:7470. doi: 10.3390/su15097470

Trust, T., and Maloy, R. W. (2017). Why 30 print? The 21st-century skills students develop while engaging in 3D printing projects. *Comput. Sch.* 34, 253–266. doi: 10.1080/07380569.2017.1384684

Walker, M., and Humphries, S. (2019). 3D printing: applications in evolution and ecology. *Ecol. Evol.* 9, 4289–4301. doi: 10.1002/ece3.5050

Wang, L., Luo, J., An, L., Zhou, X., Yin, C., and Ma, H. (2021). Promoting junior school Students' spatial ability through 3D printing. In: *2021 Tenth International Conference of Educational Innovation through Technology (EITT)* 100–105.

Wilk, R., Likus, W., Hudecki, A., Syguła, M., Różycka-Nechoritis, A., and Nechoritis, K. (2020). What would you like to print? Students' opinions on the use of 3D printing technology in medicine. *PLoS One* 15:e0230851. doi: 10.1371/journal.pone.0230851

Yan, Q., Dong, H., Su, J., Han, J., Song, B., Wei, Q., et al. (2018). A review of 3D printing technology for medical applications. *Engineering* 4, 729–742. doi: 10.1016/j.eng.2018.07.021

Ye, Z., Dun, A., Jiang, H., Nie, C., Zhao, S., Wang, T., et al. (2020). The role of 3D printed models in the teaching of human anatomy: a systematic review and meta-analysis. *BMC Med. Educ.* 20:335. doi: 10.1186/s12909-020-02242-x

Ye, Z., Jiang, H., Bai, S., Wang, T., Yang, D., Hou, H., et al. (2023). Meta-analyzing the efficacy of 3D printed models in anatomy education. *Front. Bioeng. Biotechnol.* 11:1117555. doi: 10.3389/fbioe.2023.1117555

Yıldırım, G. (2018). Teachers' opinions on instructional use of 3D printers: a case study. *Int Online J Educ Sci* 10, 304–320. doi: 10.2139/ssrn.3331158

Záhorec, J., Nagyová, A., and Hašková, A. (2019). Teachers' attitudes to incorporation digital means in teaching process in relation to the subjects they teach. *Int J Engineer Pedag* 9, 100–120. doi: 10.3991/ijep.v9i4.11064

Zhou, L.-Y., Fu, J., and He, Y. (2020). A review of 3D printing technologies for soft polymer materials. *Adv. Funct. Mater.* 30:2000187. doi: 10.1002/adfm.202000187