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Longitudinal perspectives on technology acceptance: Teachers' integration of digital tools through the COVID-19 transition

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Abstract

The rapid and continuing acceleration of digital transformation in education, propelled by the COVID-19 pandemic, has underscored the urgent need to examine how teachers adapt to and integrate digital tools in their teaching practices. Anchored in the Technology Acceptance Model (TAM) as its theoretical framework, this study uniquely uses a longitudinal design to trace the evolving patterns of technology acceptance and integration among teachers. Through qualitative methodology, involving three series of interviews with 13 secondary school teachers over two years, we identify their evolving interactions with digital tools. Our analysis reveals a cyclical pattern of technology acceptance and use across time, characterized by initial rapid adaptation to digital tools, subsequent periods of reflection and skill acquisition, and varied levels of sustained integration or reassessment. Based on our findings we propose an adapted, cyclical TAM framework and highlight the critical role of ongoing support, professional development, and infrastructure improvements, arguing for comprehensive support systems and adequate time for educators to progress through different stages of digital tool integration. We conclude that a deep understanding and support of these cycles are essential for empowering teachers to lead the digital transformation in education effectively.

Keywords TAM · Stages of transformation · Technology use · Cyclical TAM

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1 Introduction

Educational systems across the globe are faced with significant challenges in connection to digital transformation (European Commission, 2020; Ferrari, 2012). The Organisation for Economic Co-operation and Development (OECD) defines digital transformation to be the process of integrating digital technology into various aspects of an organization or society to fundamentally change how it operates, delivers value, and interacts with stakeholders (OECD, 2019). The pivotal role of teachers in driving the digital transformation of education is well recognized as a complex phenomenon (Wohlfart & Wagner, 2023; Wohlfart et al., 2023; Ertmer & Ottenbreit-Leftwich, 2010). Despite this acknowledgment, achieving a comprehensive integration of digital tools in formal education remains an ongoing challenge as this hinges on various factors such as teachers' knowledge, access, and the time available to explore these tools (Tondeur et al., 2012). Moreover, teachers' willingness and ability to integrate technology are influenced by their attitudes and personal fears (Njiku, 2022; Wilson et al., 2020). For investigating these attitudes and perceptions the widely applied Technology Acceptance Model (TAM) by Davis (1986) provides a robust framework. It posits that the perceived usefulness (PU) and perceived ease of use (PEOU) of technology are fundamental determinants of technology acceptance and, ultimately, its integration and use.

However, the integration of digital tools into education is still far from exhaustive: The International Computer and Information Literacy Study 2018 (ICILS) reported that only around 49% of teachers used digital tools on a day-to-day basis, with substantial differences in technological infrastructure and access to professional learning across countries (Fraillon et al., 2020). There seems to be a gap between intent (or ability) to integrate and the actual integration of digital tools (Lee et al., 2003; Scherer & Teo, 2019). The nuanced dynamics of teachers' technology acceptance and integration remains unknown, particularly in the context of the Covid-19 pandemic.

The outbreak of the Covid-19 pandemic in 2020 fundamentally altered the educational landscape, compelling teachers to adopt digital tools in their teaching practices. The pandemic left no choice but to embrace technology in order to continue providing quality education (Wohlfart et al., 2021). Over the following years, schools have had to adapt and re-adapt to rapidly changing situations, and teachers have been at the forefront of this digital transformation. In light of the unique challenges posed by the pandemic and the unprecedented reliance on digital tools, understanding the lasting impact of this experience on teachers' acceptance and usage of technology becomes particularly important (West, 2023).

Previous research has often relied on one-time data collection, making it challenging to identify individual dependencies in the transformation process. The present study aims to explore the longitudinal development of teachers' acceptance and use of digital tools since the outbreak of the Covid-19 pandemic. By conducting interviews with teachers at three different points over two years, this research seeks to gain insights into the dynamic nature of technology acceptance and the complex interplay of factors influencing the lasting integration of digital

tools in teaching. Through the lens of the TAM, this study contributes to a deeper understanding of the mechanisms underlying the successful digital transformation of education and the persistent challenges that need to be addressed.

2 Technology acceptance and integration

In the realm of educational technology research, the technology acceptance model (TAM) proposed by Davis (1986) has emerged as a widely recognized and extensively applied theoretical framework. The model is rooted in established psychological theories, such as Fishbein's theory of reasoned action (1980) and Ajzen's theory of planned behavior (1985). Our study builds upon an enhanced version of this model as refined by various researchers (e.g., Sánchez & Hueros, 2010; Teo et al., 2008)(see Fig. 1).

At the core of the model are the variables of "perceived usefulness" (PU) and "perceived ease-of-use" (PEOU). PU refers to a user's perception of whether technology can enhance their task efficiency. For educators, this translates to whether they believe digital tools can make their lessons more effective, for instance, by streamlining lesson preparation and delivery (Teo et al., 2008). On the other hand, PEOU reflects the user's belief in the simplicity of integrating digital tools into their classroom practices. It indicates whether the technology can be seamlessly adopted without significant effort. A lack of PEOU might lead users to realize that the technology's potential usefulness is outweighed by the complexities of its use.

The TAM also incorporates the variable "attitude toward using" (ATU), which directly emanates from PU and PEOU and explains a user's motivation for adopting a particular technology. In the educational context, ATU pertains to teachers' emotional inclination or aversion to using digital tools in their classrooms, complementing the cognitive aspects of PU and PEOU (Bresler, 2016).
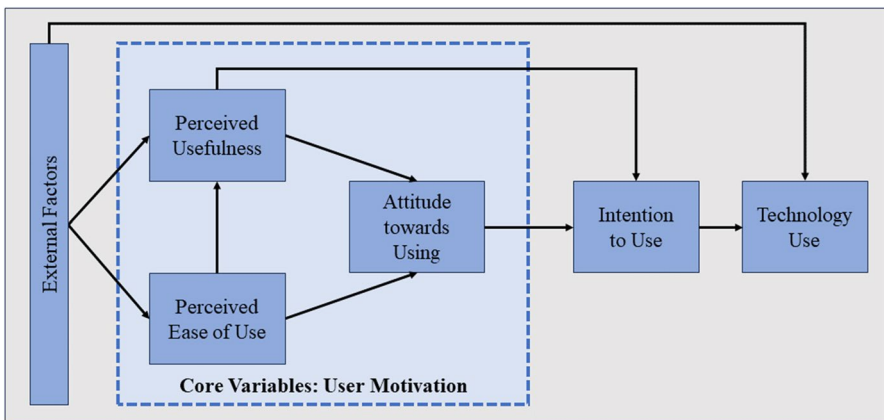

Fig. 1 Technology acceptance model (own illustration based on Davis, 1989 & Wohlfart et al., 2021)

Nonetheless, the original TAM's PU and PEOU variables alone do not fully elucidate user motives (Davis, 1986). External factors significantly influence user acceptance, depicted as "design features" on the left side of Fig. 1. These variables, such as subjective standards (perception of technology's importance to others) and self-efficacy (one's ability to handle technology), have been emphasized by Taylor and Todd (1995). To enhance the model's explanatory power, Venkatesh and Davis (2000) extended it to include social influence processes (e.g., subjective norm, voluntariness, and image) and cognitive instrumental processes (e.g., job relevance, output quality, result demonstrability). Other researchers have further explored the interplay of external variables (e.g., Burton-Jones & Hubona, 2006; Lee et al., 2003; Winarto, 2011; Wohlfart et al., 2021; Wohlfart & Wagner, 2023), emphasizing the relevance of considering additional factors.

The model defines "behavioral response" as its outcome variable, encompassing behavioral intent (BI) and technology use (TUSE). However, studies have revealed that the non-tangible BI does not necessarily translate into tangible TUSE, indicating that external variables also influence this relationship (Bresler, 2016; Scherer et al., 2019). By incorporating these refined elements and external factors into our extended TAM, we aim to provide a more comprehensive understanding of teachers' acceptance and utilization of digital tools in their educational practices.

2.1 Technology acceptance and integration in educational research

The rapid advancement of information systems and technology has necessitated the development, validation, and refinement of theoretical models to comprehend the acceptance and utilization of digital technologies in educational settings. Granić (2022) recent review of the TAM offers valuable insights into its current status in the educational field, where TAM has emerged as a prominent scientific paradigm for investigating technology acceptance among students, teachers, and other stakeholders. It is widely applied in e-learning acceptance literature, with numerous studies exploring its applicability to various learning technologies, such as mobile learning and Personal Learning Environments (PLEs) (Abdullah & Ward, 2016; del Barrio-García et al., 2015; Šumak et al., 2011). Research by Casey et al. (2023) emphasizes the role of socioeconomic factors in technology access and highlights the importance of preparing preservice teachers with the skills necessary for effective technology use in diverse educational settings.

Empirical research on TAM includes both original and extended versions of the model tested in educational contexts (Cheung & Vogel, 2013; Farahat, 2012; Park et al., 2007; Venkatesh & Davis, 2000; Zhang et al., 2008). Additionally, theoretical research, such as reviews and meta-analyses, have summarized empirical findings on specific topics within education, like teachers' adoption of technology, e-learning adoption, and TAM in m-learning environments (Abdullah & Ward, 2016; Al-Emran et al., 2018; Scherer et al., 2019).

Recent research has extended the TAM to investigate how various external factors impact teachers' behavioral intent (BI) and TUSE. Modified frameworks like TAM2 (Venkatesh & Davis, 2000) or TAM3 (Venkatesh & Bala, 2008) show

the interaction between the core TAM variables (PEOU, PU, ATU) and external factors, such as self-efficacy, university support, and social influences (Scherer & Teo, 2019). Despite various updates and the emergence of other technology acceptance models like the Unified Theory of Acceptance and Use of Technology (UTAUT; (Venkatesh & Davis, 2003; Venkatesh et al., 2016), the TAM remains a foundational model common to almost all technology acceptance models. While newer models may introduce additional variables and different assumptions on structural relations, many constructs in these models correspond to the variables included in the TAM (Teo, 2009). In this sense, the TAM serves as a core model that underlies and informs the development of various technology acceptance model. Scherer and Teo (2019) summarize three factors to influence teachers' acceptance and integration: organization, technology and individuum.

The examination of barriers to the integration of digital tools in education, alongside factors facilitating such integration, forms a crucial aspect of technology acceptance research. Among the challenges, time constraints emerge as a significant barrier to the adoption of digital tools by teachers. Wohlfart and Wagner (2023) emphasize that teachers frequently cite the lack of time as a deterrent to using digital tools effectively within the classroom environment. This issue is further compounded by the substantial time investment required to locate and vet free, high-quality educational resources, as found by Schmid et al. (2017).

(Not only) in Germany, infrastructure plays a pivotal role in the adoption and effective use of digital media in teaching. Schmid et al. (2017) report that concerns about the adequacy of technical equipment, including Wi-Fi coverage and IT support, are prevalent among educators. Nearly half of all teachers have expressed apprehensions regarding the technical infrastructure available in schools. Moreover, the scarcity of opportunities for professional development in digitalization and digital literacy remains a significant obstacle (Waffner, 2020). These infrastructural and professional development deficiencies critically influence teachers' perceptions and experiences with digital tools, potentially hindering the effective integration of such technologies into teaching practices.

Contrary to expectations, age has not been identified as a significant factor influencing teachers' attitudes towards or utilization of digital tools (Guo et al., 2008). Instead, it is the teaching experience that appears to play a more crucial role in shaping technology acceptance and integration within educational contexts (Wohlfart et al., 2021; Spiteri & Chang Rundgren, 2020). This insight challenges common stereotypes regarding generational differences in technology use and suggests that experience and familiarity with the educational system's intricacies may have a more profound impact on technology integration efforts.

A notable dichotomy exists between the intent to integrate technology and the actual integration of digital tools in educational settings. Studies have consistently shown a discrepancy between these two aspects, with intent often cited as a strong predictor of actual technology integration (Wohlfart et al., 2023; Lee et al., 2003; Scherer & Teo, 2019). This suggests a complex interplay between theoretical willingness to adopt digital tools and the practical challenges that inhibit their integration. The examination of this discrepancy remains a key area of interest

within the field of educational technology research, underscoring the need for targeted strategies to bridge the gap between intention and implementation.

The COVID-19 pandemic has significantly influenced research on technology acceptance in education, with studies focusing on the challenges and opportunities presented by the sudden shift to remote learning. Georgiou et al. (2023) highlight the importance of self-efficacy beliefs and attitudes towards computer use as predictors of technology integration during times of disruption. Meanwhile, Khong et al. (2023) extend the TAM to predict teachers' acceptance of online teaching, incorporating constructs like technological pedagogical content knowledge (TPACK) and innovativeness. These studies contribute to our understanding of the dynamic factors influencing technology acceptance and use in emergency remote teaching scenarios. The pandemic has not only tested the resilience and adaptability of educational systems but also provided insights into the conditions that facilitate or hinder effective technology integration in education.

2.2 Research gap: Technology acceptance and integration in times of Covid-19

Despite extensive research on technology acceptance, including the TAM and its refined versions (Granić, 2022; Granić & Marangunić, 2019), a significant gap remains in understanding the nuanced dynamics of technology acceptance and integration, particularly in the context of the Covid-19 pandemic. Many existing studies on technology acceptance have leaned heavily on self-reported measures of usage, which may not accurately reflect actual usage patterns. Furthermore, the predominant reliance on quantitative, questionnaire-based methodologies has constrained the depth of understanding that can be gained regarding the factors influencing technology acceptance and integration. Such approaches often fail to capture the complex interplay of individual, organizational, and technological factors that affect teachers' attitudes towards and use of digital tools in educational settings.

Addressing these limitations, our research employs a refined TAM framework to conduct and analyze longitudinal interviews with teachers from secondary schools in Germany (Teo et al., 2008; Wohlfart et al., 2021). By focusing on the actual use of digital tools in teaching and exploring the evolution of teachers' acceptance and usage over time, this study seeks to provide a richer, more nuanced understanding of technology integration in educational practices. Specifically, our study examines the following research questions (RQ):

RQ 1: How has teachers' acceptance and usage of digital tools developed across time since the outbreak of the Covid-19 pandemic?
RQ 2: Which factors influence a lasting integration of digital tools in teaching?

3 Method

In our pursuit of research questions, we conducted a longitudinal interview study in the federal province of Baden-Wuerttemberg, Germany. Schools in Baden-Wuerttemberg, mandated initially for a one-month suspension of all activities starting March 16th,

2020, remained closed for almost three months, gradually reopening for smaller student groups in mid-June 2020. By 2021, schools transitioned to a rotating system, with half the classes engaged in distance teaching while the other half attended in person. Finally, by 2022, a return to traditional face-to-face teaching was invoked.

Our study's findings, rooted in a qualitative data analysis of 35 semi-structured interviews, involving 13 teachers, spanning the years 2020–2022. The intention was to accurately depict the pandemic situation, mitigating potential delays or distortions inherent in retrospective memory dynamics (Becker et al., 2002). Conducting interviews at multiple points in time allowed us to track teachers' experiences, perceived challenges, and successes, providing a deeper understanding of their professional development. The extended timeframe, meanwhile, enabled us to observe the personal transformation processes of technology acceptance and its impact on teaching. The semi-structured interview format offered detailed insights into various topics and social settings while maintaining flexibility based on interviewee background and experience (Denzin & Lincoln, 2018).

We crafted three interview guides with slight variations in focus over the years, covering adaptation to distance teaching, technology acceptance and implementation, transformation processes in teachers' roles, and digital transformation's effects on instructional and institutional changes (cf. Table 2 in Appendix). Additionally, we employed a brief questionnaire to gather socio-demographic information. The interviews, conducted in June and July of 2020, 2021, and 2022, initially used a variety of video conferencing tools such as Skype, Zoom, and others that participants preferred. As the pandemic progressed and both participants and researchers became more accustomed to virtual interactions, we transitioned to using Microsoft Teams for the interviews in 2021 and 2022 to ensure consistency and ease of access. The interviews, ranging from 34 to 71 min each, were audio-recorded and transcribed verbatim following specific guidelines (Dresing & Pehl, 2019). De facto anonymization of the transcripts was applied to ensure confidentiality, with personal characteristics and details replaced by pseudo-information. In total, we generated 396 pages of single-spaced transcribed text, with a cumulative interview time of approximately 22 h.

3.1 Participants

A purposeful sampling strategy, inspired by Patton's (2015) methodology, guided participant selection. Teachers from Baden-Wuerttemberg instructing classes at secondary levels I and II (with students aged ten to sixteen years old) were included, ensuring diversity in professional experience and workloads related to extra-curricular activities. The summary of interviewed teachers, presented in Table 1, represents gender by letter and order of interviews conducted by number.

3.2 Data analysis

Conducting a qualitative content analysis, we applied Mayring's (2022) methodology to examine the 35 interview transcripts. This approach is grounded in the qualitative paradigm, which understands meaning and knowledge as situated and

Table 1 Participants (sorted by gender)

Pseudonym	Age*	Subjects Taught	Teaching experience (in years)*	Teaching load (in hours)**	2020	2021	2022
M01	50	Music, Physical Education (PE), Maths	14	25	✓	✓	✓
M02	45	Biology, Geography, Ethics, Science & Technology	15	25	✓	✓	✓
M03	37	Maths & PE	2	12.5	✓	✓	✓
M04	45	Maths & Geography	16	25	✓	✓	x
M05	31	Maths & PE	1	25	✓	✓	✓
M06	38	German, History, Social Studies	6	22	✓	✓	✓
M07	38	Spanish, History, Social Studies	6	24	✓	✓	✓
M08	31	Maths & PE	1	25	✓	✓	✓
F02	60	German & Geography	26	22	✓	✓	✓
F03	41	Biology, Chemistry, Science & Technology	11	16	✓	✓	✓
F04	28	Biology & Maths	0	20	✓	✓	✓
F05	28	Physics, Maths, Science & Technology	0	23	✓	✓	x
F06	38	PE & German	9	8	✓	x	x

*Sociodemographic information based on responses in 2020

**A full teaching load consists of 25 h/week

contextual (Braun & Clarke, 2020). We chose qualitative content analysis because it allows for systematic, rule-guided examination of textual data, enabling us to derive meaningful categories and patterns from the interview transcripts. This method emphasizes transparency in coding and analysis, ensuring that the findings are comprehensible and demonstrable. The researchers played an active role in this process, bringing their subjectivity and contextual understanding to bear on the interpretation of the data (Braun & Clarke, 2013).

The transcripts were thoroughly reviewed by the authors, who repeatedly read and coded specific segments using MAXQDA Analytics Pro 2022. The coding process involved applying deductive categories based on the variables of the TAM and integrating inductive categories that were generated from the transcribed interviews. These inductive categories captured personal transformation processes over time, such as professional development and reflective integration of technology. This dual approach allowed us to stay grounded in the theoretical framework while remaining open to new insights generated from the data. In the Appendix, Table 3 presents a comprehensive overview of the primary category "PU" (Perceived Usefulness), its corresponding subcategories, and detailed

definitions with anchor examples. This table serves as a reference for understanding how specific segments of the transcripts were categorized and analyzed.

To illustrate our research findings and interpretations concerning the research question, we chose excerpts from the interview transcripts. All interviews were originally conducted in German, and the first author translated selected quotes into English using DeepL. Subsequently, we critically examined these translations, ensuring the preservation of participants' voices and avoiding potential misunderstandings, following the guidelines proposed by Denzin and Lincoln (2018).

4 Findings: Transformation of technology acceptance

The findings presented in this section describe the evolving landscape of teachers' acceptance and usage of digital tools, spanning the years 2020 to 2022. The exploration examines key elements of the TAM, focusing on the motivational variables ATU, PU and PEOU as well as external factors and technology use (TUSE) that significantly shaped teachers' motivations over time.

4.1 Attitude towards using (ATU)

At the outset of the study in 2020, teachers displayed a diverse range of experiences and attitudes towards the integration of digital tools, reflecting a landscape marked by heterogeneity. However, as teachers were compelled to incorporate technology into their teaching practices, a notable shift in attitudes and experiences emerged. The initial challenges and resistance began to transform, leading to a more positive outlook in 2021. Teachers' experiences grew, and a significant number expressed a positive evolution in their digital proficiency. One participant articulated this transformation, stating, "When we first started talking, I was a digital Neanderthal. And now I'm one of those who are […] ahead digitally" (M01_2022).

Additionally, teachers collectively recognized and accepted the enduring nature of technology in education, with a prevailing sentiment that digital tools would alter the landscape of teaching: "…lessons will change fundamentally" (F05_2021). This positive trend, however, experienced a setback in 2022, as a notable backlash among some teachers emerged. This subset expressed a desire to revert to traditional teaching methods, yearning for a return to their pre-pandemic teaching routines.

The impact of attitudes on other variables within the TAM demonstrated a dynamic evolution. In the initial years (2020–2021), as teachers were compelled to undergo digital transformation, attitudes alone could not predict acceptance and integration. Instead, all teachers were required to function within the digital realm as a necessity imposed by external circumstances.

With a gradual return to normalcy in day-to-day school operations in 2022, personal attitudes towards using digital tools gained prominence. Teachers' individual preferences and comfort levels with technology began to exert a more substantial influence on the acceptance and integration of digital tools. An illustrative quote captured this sentiment: "I prefer face-to-face teaching because you can interact with

the students. Online teaching is better than no teaching, but the gaps for some students are very large" (M01_2022).

4.2 Perceived usefulness (PU)

In 2020, teachers initially emphasized the perceived usefulness (PU) of digital tools primarily for general organizational tasks within their teaching. These tasks included the preparation of materials, communication with students, and collaboration with colleagues. The utilitarian aspect of digital tools became evident as teachers, grateful that these tools enabled them to continue teaching in some capacity, primarily resorted to digitalizing their existing teaching materials and uploading them to online learning management platforms. The impact of PU extended beyond mere functionality, influencing personal attitudes. A teacher's statement exemplifies this connection: "I recognize the utility of digital media, and for that reason, I have privately acquired a laptop with a touchscreen to familiarize myself with it and not be left behind." (M01_2020).

Looking at changes over time, we identified the aspect of critically reflecting the pedagogical usefulness of digital tools. In 2020, teachers did not critically reflect on the perceived usefulness of digital tools on a didactical or pedagogical level. Some questioned the efficacy, with one teacher expressing skepticism: "The students did not learn anything from my digital teaching; I had to repeat everything in face-to-face instruction." (M01_2020). By 2021, all teachers had grown to appreciate digital tools to a certain extent, with some educators beginning to explore new opportunities for integrating technology. Reflecting this, one teacher stated, "I'm gradually trying to move to a paperless office" (M02_2021). Despite initial reservations, teachers acknowledged at least some added value in digital tools. A teacher pointed out practical benefits, stating, "I have recognized one advantage of digital media in the classroom, and that is that I can easily involve students from the quarantine in the lesson. I find that very practical because the students can then follow the lesson. […] I also realize that digital media has reduced the effort involved in other things. [For example,] It has become much easier to share content." (F03_2021).

However, in 2022, teachers engaged in a more critical reflection on the usefulness of digital technology in their teaching. Having gained confidence in traditional teaching methods, teachers began to reflect on the pedagogical implications of digital tools. This shift in understanding recognized that digital transformation surpassed mere digitalization of analog teaching materials. Teachers became more reflective, as illustrated by the following quotes: "Digital tools really simplify things in the classroom. But I have to be careful with the students that they still think along in the classroom and don't stop listening in class and rely on the digital media" (M02_2022). Another teacher noted the ongoing process of thoughtful consideration: "I perceive that more and more thought is being given to when it makes sense to use [digital tools] and how. The process is not yet complete, but it has already begun to be addressed" (M03_2022).

4.3 Perceived ease of use (PEOU)

Similar to the evolution of attitudes and PU, the perceived ease of use (PEOU) exhibited a dynamic trajectory shaped by the digital literacy of the interviewed teachers. Overall, teachers asserted that utilizing digital tools was "no rocket science" (F05_2020), emphasizing that, with some self-directed learning, they could manage these tools. However, this claim needs careful consideration, as the PEOU often centered on digital tools supporting the organizational aspects of teaching. Teachers who integrated digital tools meaningfully and purposefully into their teaching to enhance the learning process of their students were typically at a higher level of digital literacy and perceived these tools as "easy" (M02_2020, M05_2022). Additionally, technical difficulties were noted as hindrances to the perceived ease of use: "I am also bothered by the many technical barriers (poor Wi-Fi quality, devices don't always work properly, …). This prevents me from using digital media more in my lessons" (F02_2021). This acknowledgment underlines the intricate interplay between technological challenges and the PEOU in integrating digital tools into the teaching environment.

4.4 External factors

Mirroring the dynamic shifts observed in ATU, PU and PEOU, external factors played a pivotal role in shaping teachers' motivation and thereby their acceptance of digital tools across the study period.

Time emerged as the most critical external factor influencing acceptance and integration, especially for more complex tools. Teachers expressed concerns about the time and effort required to familiarize themselves with digital tools and redesign their teaching methods. In 2022, one teacher emphasized this aspect, stating, "Another aspect that speaks against the use of digital media for me is the effort involved in familiarizing myself with it and redesigning my lessons. That's why I prefer to teach as I did two years ago. If the added value of digital media was so great that it made up for the effort involved, I would use digital media more" (M06_2022).

The influence of **external support structures**, both internal and external, was notable. Technical assistance emerged as a significant external factor for teachers facing challenges. A dedicated colleague's role in simplifying PEOU was acknowledged, emphasizing the impact of collaboration within the teaching community. This internal support played a crucial role in easing the adaptation to digital tools. Simultaneously, the collective desire for a fully functional infrastructure for schools, students, and teachers highlighted the external factors influencing the potential enhancement of digital tool integration in the future. However, the communication from school leadership, though generally positive, lacked assertiveness, impacting the overall acceptance of digital tools among teachers (M09_2020).

Infrastructure's evolution over time was noted, with teachers being equipped with necessary hardware and software by 2021. However, delays in equipment acquisition impacted the timely implementation of digital tools in some cases, adding a temporal dimension to the external factors. When teachers were asked about the factors that would further enhance the integration of digital tools in the future in 2020, most pointed towards a fully functional infrastructure. The evolution of infrastructure was evident, as in 2020, some teachers lacked personal computers for online teaching, while by the second round of interviews in 2021, all teachers were fully equipped. However, on a critical note, one teacher emphasized the challenges, stating, "We have acquired some new technical devices. And of course, that also helps us now if we want to use them. However, that took a very long time and came a little late. For example, we got company iPads, but they didn't arrive in time for the start of the school year. That's why I haven't even set mine up yet and probably won't do so until the next school year" (M06_2021). Technical barriers such as Wifi connectivity issues (M07_2022) and insufficient technical support (M08_2022) continued to pose significant challenges, underscoring the gap between having access to digital tools and being able to effectively integrate them into teaching practices.

The interplay of **data privacy and security issues** as external factors was evident. In 2020, these concerns were either ignored (M09_2020) or used as excuses to justify a lack of integration (M03_2020, F02_2020). By 2021, the need for expert support in addressing data privacy concerns was emphasized, calling for intervention at the state level (M02_2021). **National and federal regulations**, or the lack thereof, influenced the usage of digital tools in 2020 and 2021. One teacher complained: „ […] very little comes from the state or the government. […] They have been relatively incompetent. Always late with their decisions. […] Until they sent out their letters. That took forever" (F03_2021). Some teachers regarded this as an opportunity to try new things and learn more about digital tools that can be used in teaching (M09_2021, F01_2020). On the other hand, being confronted by such an abundance of information and options, several teachers explained that they would like clearer guidelines from "above" (M02_2022; M03_2022).

The shifting **social norms** in 2021 emphasized the changing landscape of teaching methods, signified by the statement, "You can't come back with xeroxed slides on the overhead projector" (W02_2021). In 2022, teachers reflected on the stress factors associated with constant connectivity, highlighting the need to learn how to manage the feeling of always being available (M02_2022, M05_2022).

Furthermore, **changes in work-life-balance** emerged as a significant external factor directly influencing attitudes and indirectly affecting acceptance. At the beginning of the pandemic in 2020, teachers spoke positively about the flexibility it offered. One teacher expressed, "I can organize my daily rhythm more flexibly. That suits me much better, as I don't like working early in the morning. I can also work less during the week because I've already done that on the weekend" (M02_2020). However, as time progressed, the workload became much heavier, and by 2022, several teachers complained of very high workloads and demands. The same teacher articulated this change, stating, "The workload and effort have

become much higher. I have the feeling that I'm a teacher 24/7 and can't switch off at home at all" (M02_2022).

Collectively, these external factors contributed to the nuanced and evolving landscape of teachers' motivation and integration of digital tools over the observed period, reflecting the intricate interplay between internal and external influences in the educational environment.

4.5 Technology use (TUSE)

The exploration into the actual use of technology, or "Technology Use" (TUSE), as the concluding chapter of our findings, unveils insights into the cyclical nature of technology adoption and integration among teachers. Over the course of the study, it became evident that teachers' interactions with digital tools were not static but evolved in a cyclical feedback loop influenced by their experiences. Initially, the necessity-driven use of technology during the early stages of the pandemic led to an accelerated familiarization with digital tools. Teachers, initially hesitant or unskilled in utilizing digital platforms, found themselves increasingly reliant on these technologies for teaching continuity. This practical engagement served as a catalyst for enhancing PEOU and PU, as evidenced by one teacher's reflection: "Using the digital board and interactive quizzes has not only made my lessons more engaging but also demonstrated to me the tangible benefits of integrating these technologies into my teaching" (F04_2021).

However, as the study progressed into 2022, the analysis TUSE variable showed an interesting development: the experience of using technology began to inform and refine teachers' attitudes towards it (ATU), creating a nuanced perspective on digital integration. While some educators continued to embrace digital tools, citing improved engagement and learning outcomes, others started to question the sustainability of such high levels of technology use. A teacher elaborated: "Although I've seen how effective digital tools can be, I'm also mindful of the importance of balance. It's crucial to not let technology overshadow the human aspects of teaching" (M07_2022).

Moreover, through the longitudinal aspect of this study we identified that teachers' ongoing use of technology fostered a deeper understanding of its pedagogical value, leading to a more selective and purposeful integration of digital tools (M08_2021 & 2022). Teachers who had effectively incorporated digital tools into their instruction found themselves more inclined to experiment with and adopt new technologies (M05_2022).

The significance of external factors in shaping technology use was also prominently highlighted. Infrastructure improvements (M03_2022; M05_2021 & 2022), access to professional development (F04_2021), and the changing landscape of educational expectations (M02_2022) influenced the frequency and manner of digital tool integration. Teachers noted that supportive environments and resources were pivotal in enabling them to navigate the challenges associated with technology use, thereby influencing their continued motivation and ability to integrate digital tools effectively (F02_2022; M02_2022).

5 Discussion

Regarding RQ1, the trajectory of teachers' acceptance and usage of digital tools unfolded as a dynamic and evolving process over the examined period from 2020 to 2022. In the initial stages, marked by the outbreak of the Covid-19 pandemic in 2020, teachers exhibited a heterogeneous landscape of experiences and attitudes. Forced to integrate technology abruptly, the teaching community underwent a transformative journey. By 2021, attitudes became notably more secure and specific, with an evident growth in digital proficiency and a recognition of technology's enduring role in education. For some teachers, this led to a setback in 2022, as they expressed a desire to revert to traditional teaching methods, indicating a nuanced and varied response to the prolonged use of digital tools. The examination of the TAM variables within this longitudinal study illustrated a cyclical and evolving relationship between teachers' use of digital tools and their motivation towards technology integration. We discuss this cyclical nature to reinforce the TAM's core premise, demonstrating that actual use of technology is both an outcome and a driver of the model's motivational variables, highlighted by the continuous influence of external factors.

5.1 Cyclical dynamics of digital tool integration in education

In the initial stages of our study (2020–2021), the collective imperative for digital integration underpinned by external circumstances highlighted that attitudes, while significant, were not sole predictors of acceptance and integration. This observation supports the contention that external pressures, such as those experienced during the pandemic, necessitate a broader, more adaptive framework for understanding technology acceptance (Wohlfart et al., 2021). As we moved towards a semblance of normalcy in 2022, we observed a shift where personal attitudes and experiences with technology began to play a more definitive role in its acceptance and integration. This shift from a collective to an individualized approach to technology integration underscores the evolving nature of technology acceptance among teachers, aligning with insights from Khong et al. (2023) on the impact of TPACK, PU, and innovativeness.

Our study provides a unique contribution to the literature on technology acceptance and integration in education by capturing a longitudinal perspective during the COVID-19 pandemic. This period accelerated the digital transformation in education, offering a distinct environment to study how teachers adapt and integrate digital tools over time. This longitudinal aspect enriches the TAM by highlighting the cyclical feedback loop between the core variables and actual technology use (Fig. 2). Continuous engagement with digital tools influenced teachers' ATU, PU, and PEOU, which in turn shaped further technology use. This suggests that as educators' self-efficacy towards digital tools increases, their attitudes and pedagogical beliefs play a more significant role in technology acceptance and integration.

The cyclical TAM process, driven by the continuous use of digital tools and influenced by core TAM variables, reflects the dynamic nature of technology acceptance
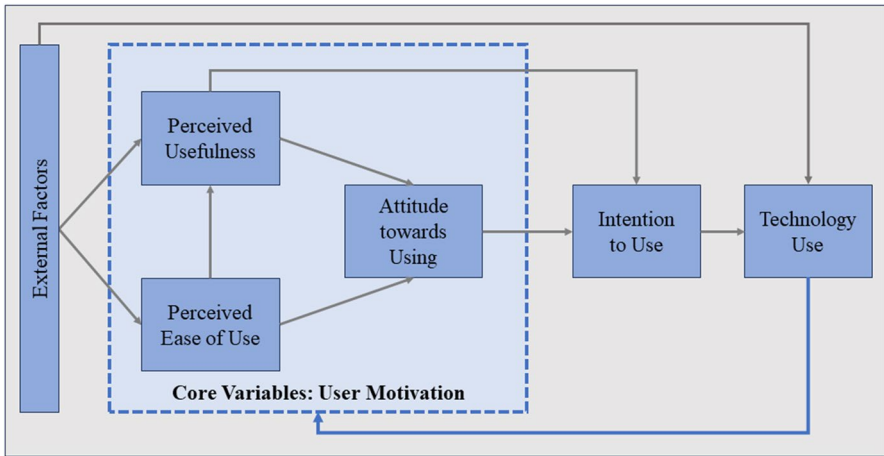
Fig. 2 Cyclical technology acceptance model with focus on technology use (own illustration)

as highlighted by Granić (2022). Understanding the cyclical process of acceptance, use, and integration is crucial for sustaining technology integration in education. This cycle stresses the importance of not only introducing digital tools but also ensuring they are perceived as useful and easy to use by educators, facilitating a positive feedback loop that enhances acceptance and integration over time.

In this context, the findings from Müller and Leyer (2023) provide an interesting parallel to our study, despite their focus on higher education teachers rather than schoolteachers. Their work emphasizes the significance of time as a critical factor in the intention-behavior gap concerning technology use. They observed that only the one-time effort to become familiar with digital elements has a significant impact on their actual usage, suggesting that, regardless of the educational level, the initial effort in familiarization with digital tools is paramount for their effective integration. This necessity points to a broader educational challenge: creating opportunities for teachers to engage deeply with digital technologies. By creating scenarios where teachers are 'forced' to practice with digital technologies, both the intention-behavior gap and the inherent willingness and developed competencies of teachers for effective digital tool integration could be addressed.

The rapid integration of digital technologies into teaching practices has raised significant concerns about data privacy among educators. As teachers navigate digital tools that extend into their personal lives, the need for robust data protection measures becomes increasingly important. Our participants frequently mentioned anxieties about data security, underscoring the critical need for institutions to provide clear guidelines and support in this area. Additionally, the shift to digital teaching and communication with students and colleagues have blurred the boundaries between work and personal time, leading to increased workload and stress for educators. Unlike earlier studies on ICT adoption, our findings reveal that teachers now face continuous demands on their time, with digital tools facilitating constant connectivity. Addressing these challenges requires institutional strategies to support teachers in managing their workloads and maintaining a healthy work-life balance.

The role of supportive external factors, such as professional development opportunities, infrastructure quality, and administrative support, in influencing the sustainability of technology integration is critical (and often ignored by research on technology acceptance and integration). A sustainable integration of digital tools in an ever-changing digital world requires an ecosystem that empowers and supports teachers' ongoing learning and adaptation, including access to high-quality digital resources, training programs, and institutional support (Myyry et al., 2022). The significant impact of time as an external factor on technology integration aligns with the concerns raised by Wohlfart et al. (2023), Wohlfart and Wagner (2023), and Schmid et al. (2017), who noted that teachers often face time constraints that hinder their ability to use digital tools effectively. The complexity of digital tools and the time required to master them can serve as barriers to their integration, suggesting the need for more intuitive and user-friendly educational technologies. Addressing these temporal challenges requires a balance between introducing innovative digital tools and providing adequate training and support to ensure their effective and sustainable integration. For practical application, this yields a straightforward yet profound insight: Recognizing teachers as key agents of digital transformation in education necessitates providing them with adequate time and sustained support. This approach enables teachers to not only learn and adapt to the use of digital tools but also to engage in critical reflection on their integration into pedagogical practices.

5.2 Stages of transformation

By exploring the cyclical dynamics of technology acceptance and integration of this sample over the past two years we identified a large spectrum of individual professional development among teachers. Marked by diverse and individual transformations, our findings underscore the relationship between teachers' previous knowledge, attitudes, and their evolving acceptance and integration of digital tools in their pedagogical practices. The longitudinal nature of this study has been pivotal in capturing these transformations, revealing distinct stages of adaptation, growth, reflection, and for some, resistance, against the backdrop of evolving educational landscapes (Fig. 3).

Ertmer and Ottenbreit-Leftwich (2010) emphasized that teachers' adaptation to technology is deeply influenced by their beliefs and the educational culture. In the wake of the pandemic's onset, teachers, irrespective of their prior digital fluency, found themselves at a crossroads, navigating the sudden imperative to employ digital tools. This **initial exploration and adaptation** phase was driven by necessity of TUSE, mirroring the adaptive phase discussed by Granić (2022). The diverse responses during this period reflect the foundational stages of technology acceptance, where the PU and PEOU begin to shape initial attitudes towards digital integration.

As educators progressed beyond initial exploration, a phase of intensive **skill acquisition and confidence building** evolved (Myyry et al., 2022). This stage
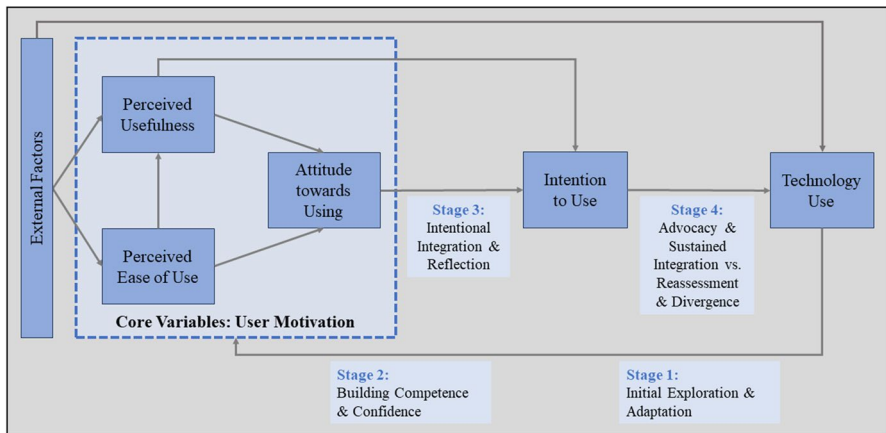
Fig. 3 Stages of transformation – an evolving spectrum of digital tool integration (own illustration)

saw educators deepening their engagement with digital technologies, often through self-directed learning, professional development opportunities, and collaborative exchanges. The commitment to enhancing digital literacy during this phase highlights the pivotal role of professional development in bridging the gap between theoretical intent and practical application (Müller & Leyer, 2023).

Armed with enhanced digital competencies through TUSE, teachers entered a phase of **intentional integration and reflection**, marked by a strategic and reflective application of digital tools. This stage is distinguished by a critical evaluation of the pedagogical value of technology, possibly transitioning from an exploratory use to a more deliberate and targeted intention to integrate informed by pedagogical goals and the dynamics of student engagement (Wohlfart & Wagner, 2023; Wohlfart et al., 2023).

For most of the interviewed educators, the journey culminated in a deep, **sustained integration** of digital tools, accompanied by a role as **advocates for technology-enhanced learning**. This advocacy, supported by a robust digital pedagogy, extends beyond personal classrooms to influence broader educational practices, encouraging a culture of sharing and collaborative growth within the educational community (Hew & Brush, 2007; West, 2023). However, not all trajectories led towards sustained integration. Post-return to face-to-face teaching, a subset of educators embarked on a path of **reassessment** and, in some cases, **divergence** from digital tool use. This stage, absent in many discussions, represents a critical reflection on the necessities of digital integration vis-à-vis traditional teaching paradigms. Teachers in this category often cited a perceived disconnect between the benefits of digital tools and the intrinsic values of in-person teaching, echoing a sentiment of digital fatigue and a yearning for pre-pandemic pedagogical approaches (West, 2023).

Our findings align with and extend several established models of ICT integration in education. The Apple Classroom of Tomorrow (ACOT) Model

(Dwyer, 1994)., for instance, identifies stages of teacher development with technology that parallel the phases observed in our study. However, the pandemic-induced rapid shift to online teaching compressed these stages, intensifying the initial adaptation and skill acquisition phases. Similarly, the Levels of Technology Implementation (LoTI) Model (Moersch, 1995, 2001) offers insights into different levels of technology use and the transformation of pedagogical practices. The added value of our study lies in its contextual specificity, temporal dynamics, and comprehensive analysis of external factors. Unlike the ACOT and LoTI models, our research captures the rapid digital transformation during the COVID-19 pandemic, providing valuable insights into how external crises influence technology adoption.

6 Limitations and outlook

The longitudinal design of our study offers a unique vantage point, revealing not just the cyclical nature of technology acceptance as theorized by the TAM, but also the spectrum of teacher responses over time. This exploration shows the importance of acknowledging diverse teacher experiences and the need for supportive frameworks that accommodate varying paths of digital integration, fostering an inclusive approach to technology acceptance in education. In considering our findings, we also acknowledge accompanying limitations.

First, the study's reliance on a small sample of longitudinal interviews, while providing in-depth individual perspectives, has its limitations. While this may decrease the perceived relevance to some, we believe that this longitudinal methodology allowed us to develop a relationship with the participants and foster an atmosphere of openness and honesty. To establish rapport and build trust with the participants, we conducted multiple interviews with each individual over an extended period of time. By engaging in ongoing dialogue and revisiting topics, we aimed to encourage participants to share their genuine experiences and feelings, even if they deviated from societal norms or expectations. Additionally, it is important to clarify that in the first round of interviews, we used a variety of video conferencing tools, including Skype, Zoom, and others preferred by the participants. This approach allowed us to capture a broad range of experiences and technological competencies, including technology-critical affinities, as exemplified by one participant mentioning it was their first video call ever. As the pandemic progressed, we transitioned to using Microsoft Teams in the second and third years for consistency and ease of access. This diversity in technological competencies provides valuable insights despite potential biases. The experiences and attitudes of the 13 teachers interviewed offer a rich, though not representative, picture of the broader population of educators at various levels of education or in different geographical locations. Expanding the sample size and employing mixed-methods approaches could allow for a more systematic examination of external factors influencing technology acceptance.

Second, the study's focus on a specific time frame, from 2020 to 2022, captures a unique period of emergency remote teaching and the subsequent transition phases. While this period offers valuable insights into the adaptation and integration processes of digital tools in education, it also means that the findings are contextually bound to the specific challenges and circumstances of the pandemic. The evolving nature of technology and pedagogical practices may present new challenges and opportunities that were not captured within the scope of this study. To deepen our understanding of technology integration in education, future studies could benefit from directly comparing the stages of transformation observed with established models like SAMR (Hamilton et al., 2016) and TPACK (Koehler & Mishra, 2009). Such analysis would provide additional layers of understanding regarding the facilitators and barriers to sustainable digital tool integration, enhancing the theoretical and practical relevance of the findings.

Third, the study focused primarily on teachers' perspectives and experiences, with less emphasis on the students' perspectives on technology usage and its impact on their learning. Including student perspectives could provide a more holistic view of the digital transformation in education and offer insights into the effectiveness of technology integration from the learners' viewpoint.

Finally, while the study acknowledges the importance of external factors such as institutional support, professional development opportunities, and infrastructure quality, it did not systematically measure these variables. Additionally, we did not collect detailed data on participants' computer literacy and technology affinity, which could have provided a broader evaluation of the study outcomes. Future studies should include these factors to enhance the understanding of technology acceptance and integration. Systematically measuring the impact of professional development, institutional support, and infrastructure quality may better inform the development of targeted interventions to support teachers in their digital integration efforts.

Appendix

Table 2 Overview of interview guides focusing on distance teaching, technology acceptance, and the impact of digital transformation on teaching and institutional practices

Year	Focus	Main Questions
2020	Adapting to distance teaching; technology implementation and acceptance; transformation of role as teacher	How are you experiencing the situation without face-to-face teaching? How was the transition to digital teaching organized in your school? How was the transition to digital teaching for you personally? How do you currently perceive the use of digital media in your teaching? How has the use of digital media during the COVID-19 period changed your role as a teacher? How does the absence of face-to-face teaching affect your personal life? What role do digital media play in your personal life? How will the integration of digital media be in the upcoming face-to-face teaching? If you had unlimited resources, what would your ideal digital solution for your school look like in order to enhance the effectiveness of your job?
2021	Implementation of digital media in teaching; classroom disruption; digital transformation process	How have you been as a teacher since our last conversation? Which digital media are you currently using in your teaching? How do you currently perceive the use of digital media in the classroom? Based on the results of last year's interviews, we found that certain factors have a significant influence on the actual integration of digital media: - For example, regulations and guidelines from the school management played a crucial role in your own use of digital media. How do you assess this in your case? - The available technical infrastructure also played a significant role. Have there been any changes for you in the past year? - Finally, some teachers mentioned the significant heterogeneity of students as a barrier to the free use of digital media. What does that look like today? What new digital experiences/tools (from online teaching) will you continue to implement after the pandemic?
2022	Technology acceptance and digital transformation	What does your current professional daily routine as a teacher look like? Which digital media do you currently use in your teaching? And how? How do you currently perceive the use of digital media in the classroom? What would currently help you to use digital media better/more/following a more meaningful approach? Which factors currently have the strongest influence on your use of digital media? (Questions regarding identified external factors: (1) Regulations and guidelines, (2) Technical infrastructure, (3) Heterogeneity of students and teachers/colleagues) What changes/developments regarding digitalization come to mind? What role did the school management play in this transformation process over the past two years?

Table 3 Exemplary overview of the main category "Perceived Usefulness" and accompanying subcategories of the interviews as well as associated definitions and anchor examples

Main Category	Definition Main Category	Subcategory	Definition Subcategory	Anchor Example
Perceived Usefulness	Statements relate to the degree to which the teacher believes that the use of digital tools creates added value/ benefits. This category captures the essence of how teachers perceive the advantages of integrating digital solutions into various aspects of teaching and learning	Modification of instructional formats	Refers to the teacher's recognition and evaluation of the benefits derived from altering traditional teaching methods to include or emphasize new instructional strategies	"And I would indeed like to use it somehow according to this flipped classroom principle. And just also, if I imagine that next year, or in two years, it doesn't matter when, I get an eighth grade again, then I would definitely run this unit according to the flipped classroom principle. Because I really see a lot of advantages in it. Especially for the subject of mathematics. So, giving input at home and practicing and repeating in school." (M05_2020)
		Sustained Digital Communication and Collaboration	Refers to the teacher's anticipation and valuation of continued use of digital tools for enhancing communication and collaboration within the educational context	"I assume that we will still have Teams. [...] As a medium for students to contact us more quickly. Or to really maybe bring [sick] students into the classroom more quickly and so on." (F03_2021)
		Creative Digital Content Creation	Refers to the teacher's recognition of the potential and future importance of leveraging digital tools for creative expression and educational content development	"... when making film music. I shoot a little film, compose some music, and lay it underneath. Brilliant. So, that is, I think, that will be the future. [...] Because my older colleagues and I were just too comfortable and didn't get off our butts to start working on these things. And we all had to do that now. And now many see the advantage, and I mean everyone, everyone." (M01_2020)
		Immersive Learning Experience	Refers to the teacher's recognition of the significance of employing immersive learning strategies to deepen students' engagement and understanding. T	"Recently in history, I worked with a relatively new app. With a VR app, that is, Virtual Reality, which was about projecting reports from Holocaust survivors into the classroom, so projecting the person into the classroom with the iPad, who then tells something and makes this report feel authentic. So, this is something that naturally engages the students in a completely different way than if you were just to play an audio file or a video, which they can control themselves and project and then work through on their own." (M07_2022)
		Digital Organization and Planning Tools	Refers to the teacher's acknowledgment of the benefits and advantages of using digital applications and platforms for organizing and planning their teaching schedules, including lesson plans and substitute arrangements	"I now have an app where I can really see my schedule, even when there are substitutions, I see them. That's not bad. It allows you to plan the week in advance. That definitely has its advantages. And a substitution plan, of course, I also have digitally accessible now. But that was accessible before via the homepage too. So, yes, it's now even faster and with less effort. Also, all the appointments are now digital in the calendar. I have such a calendar. In all also, I have to say, was really brilliant." (F03_2022)

Data availability The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

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