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A unified framework for understanding teachers' adoption of robotics in STEM education

Hüseyin Ateş[1] · **Cengiz Gündüzalp**[2]

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Abstract

Robotics, an emerging tool in STEM education, promises a multitude of educational benefits, ranging from hands-on learning experiences to fostering critical thinking and collaborative skills. However, the integration of robotics in classrooms is primarily contingent upon science teachers' inclination and willingness to adopt this technology. To bridge this gap, this research aimed to explore the adoption of robotics within STEM education by science teachers, by merging the Theory of Planned Behavior, Technology Acceptance Model, and Self-Determination Theory into a unified conceptual framework. Our hypothesis-driven approach tested using data from 605 science teachers across various regions in Turkey. The results indicate a significant positive correlation between science teachers' perceptions of the usefulness and ease of use of robotics and their intent to adopt it in their classrooms. Moreover, intrinsic motivational factors such as perceived autonomy and relatedness played a pivotal role in influencing teachers' behavioral intention towards robotics. The findings revealed that, compared to existing theories, our unified model offers a heightened understanding of the determinants influencing teachers' intentions to use robotics in STEM education. Ultimately, our research not only paves the way for a theoretically enriched understanding of technology adoption in STEM but also presents actionable insights for educators, curriculum designers, and policymakers aiming to capitalize on the myriad opportunities offered by robotics in contemporary education.

Keywords Robotics based STEM education · Science teachers · Theory of planned behavior · Technology acceptance model · Self-determination theory · Teacher adoption

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✉ Hüseyin Ateş
huseyin.ates@ahievran.edu.tr

[1] Department of Science Education, Kırşehir Ahi Evran University, Kırşehir, Turkey

[2] Department of Computer Technologies, Kazım Karabekir Vocational School of Technical Sciences, Kafkas University, Kars, Turkey

1 Introduction

In recent times, the integration of robotics within STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a transformative educational strategy, drawing attention from both academic and professional realms (Armstrong & Tawfik, 2023; Chauhan & Kapila, 2023; Darmawansah et al., 2023). Robotics, when seamlessly infused into the curriculum, not only enriches the technical proficiency of students but also fosters creativity, critical thinking, and problem-solving abilities - essential skills for the 21st century (Chesloff, 2013; Convertini, 2021). Science teachers play a pivotal role as change agents in schools, driving the innovative integration of robotics into STEM education (Baran et al., 2020; Çetin & Türkan, 2022; Sahin & Yilmaz, 2020). However, their adoption and implementation of this technology are not without challenges. They often encounter obstacles such as a lack of resources, insufficient training, and concerns about the efficacy of robotics in educational settings (Sungur Gül et al., 2023). While these teachers' decisions are influenced by a range of factors, there remains a significant gap in understanding the deeper psychological drivers affecting their adoption choices. The benefits and obstacles of using robotics in STEM education are evident, but a more thorough exploration of the underlying psychological factors influencing science teachers is still needed.

Previous research has separately delved into the factors influencing science teachers' behavioral intentions in the scope of STEM education such as the Theory of Planned Behavior (TPB) (Cheung & Tse, 2021; Li et al., 2019; Lin & Williams, 2016) and the Technology Acceptance Model (TAM) (Sungur Gül & Ateş, 2023). Additionally, intrinsic motivation, as defined by the Self-Determination Theory (SDT), has been identified as a potent force in guiding teachers' choices and actions in the STEM Education (Chiu, 2023). Despite the significance of these individual theories, limited number of studies have amalgamated them to provide a holistic understanding of the adoption process of robotics in STEM education by science teachers. Some research merged TAM and TPB to understand teachers' adoption within the context of science education (Ateş & Garzón, 2022) but hasn't incorporated the motivational elements presented by SDT. Therefore, there's an apparent gap in presenting a unified conceptual framework that would comprehensively capture the multidimensional influences on the said adoption process.

With this backdrop, the current research distinguishes itself from prior works in multiple ways. Firstly, this study pioneers the integration of TPB, TAM, and SDT into a unified, comprehensive framework specifically tailored for understanding robotics adoption in STEM education. Secondly, we emphasize the dual facets of adoption - the perceived usefulness (PU) and perceived ease of use (PEU) (from TAM) and autonomy, competence, and relatedness (from SDT) - alongside the components of TPB including attitude (ATT), subjective norm (SN), and perceived behavioral control (PBC). Thirdly, this research explores the complex interplay among these constructs and examines their collective impact on science teachers' intentions to adopt robotics in STEM education. While existing research has explored the roles of TPB, TAM, and SDT within the broader field of educational technology (Ateş & Yılmaz, 2023), our study distinguishes itself as one of the first to amalgamate these theories into a comprehensive model specifically tailored for understanding robotics adoption in STEM education. This enables us to more accurately identify a range of factors affecting teachers' adoption decisions regarding robotics in STEM education.

Overall, our objective is to develop a versatile and robust model that is tailored for the field of science education, specifically targeting the incorporation of robotics into STEM curricula. This research pioneers the integration of TPB, TAM, and SDT into a unified framework, thereby offering a more comprehensive understanding of the diverse psychological and behavioral factors affecting science teachers' adoption of robotics in STEM education. The study sets out to:

1. Develop a unified model that encapsulates the combined insights of TPB, TAM, and SDT, offering a deeper understanding of science teachers' adoption of robotics in STEM education.
2. Determine the relative importance of this unified model as compared to the standalone impacts of TPB and TAM.
3. Examine the relative importance among constructs including attitude, subjective norm, perceived behavioral control, and perceived usefulness within our unified framework to identify the intention.
4. Delve into the possible mediating roles of constructs including perceived usefulness, perceived ease of use, and attitude to identify the intention.

2 Literature review

2.1 Robotics in STEM education

The role of robotics in STEM (Science, Technology, Engineering, and Mathematics) education has evolved significantly, offering a multidisciplinary and interactive approach to traditional learning. This amalgamation has been especially beneficial in enhancing the STEM curriculum by providing real-world applications and fostering a culture of creativity, critical thinking, and collaboration among students. According to Chiang et al. (2020), Guven et al. (2020), and Sen et al. (2021), the strength of STEM education lies in its process-oriented approach which already offers avenues for creativity and critical thinking. However, the challenges of unfamiliar content, unstructured activities, and inadequate curricula have hampered its full potential (Conde et al., 2021; Moomaw, 2012; Sarama & Clements, 2009). Addressing these challenges, robotics has emerged as a methodological catalyst that complements and enriches traditional teaching methods in STEM education (Bargagna et al., 2019). In terms of cognitive development, research shows that students exposed to robotics experience enhanced problem-solving scenarios demanding critical thinking, logical reasoning, and higher-order skills (Gomoll et al., 2017; Sen et al., 2021; Stewart et al., 2021). Further studies indicate that robotics integration can ignite curiosity (Adams et al., 2011), improve psychomotor skills (McDonald & Howell, 2012), and strengthen logical reasoning (Bers, 2008). In the realm of social skills, robotics has shown considerable promise in promoting teamwork and collaboration (Convertini, 2021). Students often work together to design, build, and program robotic models, thus fostering interpersonal skills essential for career development in STEM fields (Ayar, 2015). This synergy between robotics and STEM education not only fulfills the curricular objectives but also extends into life skills such as teamwork, problem solving, and project management (Convertini, 2021; Ucgul & Altıok, 2022). On the practical side, robotics tools and platforms are diverse and customizable. Elementary schools often use basic robotic tools like Bee-Bots and LEGO WeDo kits to introduce young learners to fundamental engineering and programming concepts (Bowen et al., 2023; Chapman et al., 2020; Guven et al., 2020; Ponce et al., 2019; Stewart et al., 2021). In middle and high schools, students get to work with more advanced platforms like Arduino and Raspberry Pi, enhancing their understanding of complex engineering principles, electronics, and intricate coding skills (Chang & Chen, 2020, 2022; Perez & Lopez, 2019). At the tertiary level, robotics often forms an integral part of specialized courses involving machine learning, automation, and artificial intelligence (Hwang et al., 2020). This progressive complexity across educational levels enriches engineering concepts and interdisciplinary practices within STEM (Luo et al., 2019).

Despite its merits, the integration of robotics into STEM education is not without challenges. High costs associated with purchasing robotic kits and the specialized training required for educators are notable obstacles (Sungur Gül et al., 2023). However, recent studies indicated that the trajectory of technological advancements and a global focus on STEM education suggest that robotics is poised to become an increasingly integral component of academic learning (Çetin & Demircan, 2020; Darmawansah et al., 2023; Guven et al., 2020; Xu & Ouyang, 2022).

Certainly, while there is a burgeoning body of literature in the domain of robotics in STEM education, a significant gap remains in comprehending how teachers perceive and adopt robotics as a pedagogical tool in their STEM classrooms. This is particularly important because teacher adoption often acts as a critical lynchpin in the successful integration of innovative technologies into educational settings. Despite the wealth of studies underscoring the benefits of robotics in STEM education (Adams et al., 2011; Evripidou et al., 2020), there is a dearth of research focusing on the factors that influence teachers' willingness to adopt robotics-based instructional methods. Understanding these factors is essential for promoting a more widespread and effective implementation of robotics in STEM education. Teachers' perspectives can play pivotal roles in determining whether robotics-based STEM education moves from the margins to the mainstream (Atman Uslu et al., 2022). Moreover, as teachers are critical agents in curriculum delivery, their confidence and competence in using robotics directly affect the quality of STEM education. Teachers' pedagogical beliefs, their comfort with technology, as well as their views on the relevance and applicability of robotics in achieving educational objectives, are areas that require thorough investigation. These dimensions not only contribute to the individual classroom experience but also have broader implications for curriculum development, professional development programs, and educational policy.

To address this notable gap, the present study seeks to investigate the adoption of robotics by science teachers within the context of STEM education. By focusing on this under-explored area, our research aims to offer a more comprehensive understanding of robotics' role in STEM educational settings.

2.2 The research model and hypotheses

2.2.1 Self-determination theory

SDT is a contemporary framework that posits individuals are innately inclined toward intrinsic motivation, with two core types of motivation: intrinsic and extrinsic (Deci & Ryan, 1985). Extrinsic motivation refers to actions undertaken for outcomes separate from the activity itself (Ryan & Deci, 2000), while intrinsic motivation is driven by the inherent pleasure and satisfaction derived from the activity (Gomez et al., 2022; Nikou & Economides, 2017). SDT suggests that intrinsic motivation is more likely to be fostered when three basic psychological needs—autonomy, competence, and relatedness—are satisfied (Deci & Ryan, 1985).

Perceived Competence (PC) can be defined as the multifaceted ability to successfully and professionally execute a task or engage in an activity within a given environment (Deci & Ryan, 1985). In the context of learning activities, it extends to being effective in achieving one's goals or desires while participating (Nikou & Economides, 2017). This suggests that competence is not just a skill set but also includes the motivational aspects that drive an individual to apply those skills effectively. Within the context of educational technology-enhanced environments, PC is closely related to PU and PEU (Ateş & Yılmaz, 2023). Several studies indicate that PC directly influences both PU and PEU (Teo & Van Schalk, 2009), although some research suggests no relationship between PC and PU (Nikou & Economides, 2017). In the context of robotics-based STEM education, this study hypothesized that science teachers' PC would influence their PU and PEU. Therefore, this study hypothesizes:

H1: A high level of perceived competence positively correlates with the perceived usefulness of robotics-based STEM technology for science teachers.
H2: A high level of perceived competence positively correlate with the perceived ease of use of robotics-based STEM technology for science teachers.

Autonomy recognized as a vital human need closely associated with positive educational outcomes refers to the individuals' capacity for self-regulation in their interactions with technology (Ateş & Yılmaz, 2023). The presence of PA is posited to elevate both intrinsic and extrinsic motivation among students, as supported by existing theories (Ryan & Deci, 2000). Active learning strategies, especially when contextualized in real-world scenarios, further bolster this sense of autonomy (Zhang & Zhou, 2022). Prior research indicates that PA correlates with PU (Fathali & Okada, 2018; Roca & Gagné, 2008), and to some extent with PEU (Roca & Gagné, 2008). However, Fathali and Okada (2018) argue that the empirical evidence linking PA and PEU remains limited. In this study, it is hypothesized that PA influence both PU and PEU among science teachers engaged in robotics-based STEM education. Based on prior research, the study hypothesizes:

> H3: A high level of perceived autonomy positively correlates with the perceived usefulness of robotics-based STEM technology for science teachers.
> H4: A high level of perceived autonomy positively correlates with the perceived ease of use of robotics-based STEM technology for science teachers.

Perceived Relatedness (PR) refers to an individual's sense of connection and encouragement from important people in their lives, such as peers, parents, or teachers (Zhang & Zhou, 2022). In the context of intrinsic motivation, relatedness is pivotal; individuals are more likely to be internally motivated when they perceive a supportive and positive environment around them (Zhao et al., 2011). Roca and Gagné (2008) posited that students who feel a sense of relatedness are more likely to find learning activities useful. Nikou and Economides (2017) demonstrated that relatedness significantly affects both PEU and PU in learning activities. In the educational technology sphere, particularly in the realm of robotics-based STEM education, PR may gain an added layer of significance. Educational technologies often incorporate collaborative features, such as discussion boards or group projects, that can amplify the sense of relatedness among learners. When individuals feel closely connected and supported by peers, mentors, and educators in a technologically-mediated environment, their intrinsic and extrinsic motivation tends to increase, thus potentially enhancing their educational outcomes (Zhang & Zhou, 2022). The concept of PR also extends to social influences that can affect users' perceptions of the technology's utility. In a study by Ateş and Yılmaz (2023), it was found that social influence, a factor closely related to PR, significantly influences teachers' PU. Therefore, in this study, we hypothesize that teachers are more likely to find an educational technology tool, such as robotics software or hardware, useful if they feel connected and supported within their learning community. In light of these discussions, the present research hypothesizes:

> H5: A high level of perceived relatedness positively correlates with the perceived usefulness of robotics-based STEM technology for science teachers.
> H6: A high level of perceived relatedness positively correlates with the perceived ease of use of robotics-based STEM technology for science teachers.

2.2.2 Technology acceptance model

TAM posits that the closest predictor of technology usage is one's behavioral intention (Davis, 1989). This intention is widely acknowledged as a key factor in technology adoption and has been validated as a strong predictor of actual usage. According to TAM, behavioral intention is shaped by two core beliefs: PU and PEU (Davis et al., 1989). PU is the belief that using a particular technology will improve one's ability to complete tasks, while PEU is the belief that using the technology will not require a lot of effort (Asmara & Ratmono, 2021). Additionally, the model suggests that if a technology is perceived as easy to use, it is also likely to be seen as useful (Davis, 1989).

TAM has been extensively validated in various educational technology contexts, ranging from mobile learning (Al-Rahmi et al., 2022) and augmented reality (Papakostas et al., 2022) to distance education platforms (Al-Dokhny et al., 2021) and Web 2.0 technologies (Teo et al., 2019). Its adaptability has also been demonstrated in STEM education; for example, Sungur Gül and Ateş (2022) utilized TAM to assess the impact of a technology-based STEM education-training program on pre-service science teachers. Their findings indicate that the model's predictive power was significantly enhanced post-training, particularly in terms of teachers' PU and PEU of technology, as well as their ATT and intentions towards implementing technology-based STEM education. A study conducted by Mutambara and Bayaga (2021a) offered several important insights into the acceptance of mobile learning in rural high schools for STEM education. Utilizing a model based on the TAM, the research successfully accounted for 40.8% of the variance in behavioral intention to adopt mobile learning among students, teachers, and parents. The foundational variables of TAM were not only directly related to the behavioral intention but also served as mediators between external factors and this intention.

In addition, there is compelling evidence that the incorporation of robotics into STEM education positively impacts teaching methods and fosters various skill sets such as computational thinking, creativity, and problem-solving in students (Adams et al., 2011; Bargagna et al., 2019; Evripidou et al., 2020; Ferreira et al., 2018; Kennedy et al., 2015). Anwar et al. (2019) highlight robotics as an effective tool for attracting learners who might initially be disinterested in STEM disciplines. Despite these advancements and the promising role of robotics in enhancing STEM education, there remains a gap in the literature concerning the factors that influence teachers' adoption of robotics-based STEM education. Based on the above arguments, the following hypotheses are formulated:

> H7: A high level of perceived ease of use positively correlate with the perceived usefulness of the technology for science teachers.
> H8: A high level of perceived ease of use positively correlates with the attitude towards adopting robotics in STEM education.
> H9: A higher level of perceived usefulness positively correlates with the attitude towards incorporating robotics into STEM education.
> H10: A higher level of perceived usefulness positively correlates with the teachers' intention to adopt robotics in their STEM educational practices.

2.2.3 Theory of planned behavior

TPB stands as a paramount model in rational choice theory, shedding light on the intricate pathways of individual decision-making. Originating from Ajzen's work in 1985, it can be viewed as a broader perspective on the theory of reasoned action, introduced by Fishbein and Ajzen (1975). In the TPB framework, the immediate predictor of a person's actions is their intention towards performing that action. This intention is shaped by their ATT towards the behavior, influenced by SN, and their

PBC to execute it (Ajzen, 1991). Attitude toward the behavior denotes "*the degree to which a person has a favorable or unfavorable evaluation or appraisal of the behavior in question*" (Ajzen, 1991, p. 188). This construct captures an individual's personal feelings or judgments about performing a particular action. Second construct is SN, which represents "*the perceived social pressure to perform or not to perform the behavior*" (Ajzen, 1991, p. 188). It underscores the influence of social factors, peers, or significant others on an individual's decision-making process. Last construct in the theory is PBC, which highlights "*the perceived ease or difficulty of performing the behavior*" (Ajzen, 1991, p. 188). This construct emphasizes an individual's belief in their capability or autonomy to execute a given action.

The TPB suggests that ATT, SN, and PBC emerge from specific beliefs: behavioral, normative, and control beliefs, respectively (Ajzen, 2006). Unlike its predecessor, the theory of reasoned action—which centered around volitional elements such as beliefs leading to ATT and SN—the TPB includes both volitional and factors beyond one's control (Ajzen, 1991). This added construct, emphasizing perceived control, enriches the theory, enabling it to better anticipate intentions and behaviors that might not be purely volitional (Han & Kim, 2010).

Over time, the effectiveness of the TPB in explaining a wide range of behaviors has been confirmed across diverse educational technology settings (Habibi et al., 2023; Wang, 2023). Specifically, because of its efficacy in predicting intentions, the TPB has been adeptly used across numerous educational technology facets in science education. Al Breiki et al. (2023) focused on understanding the behavioral intentions of science teachers in Oman to use virtual reality in their classrooms. Based on the TPB, the study analyzed data from 171 science teachers and found that ATT, SN, and PBC significantly influence their intentions to use virtual reality in the classroom. Among these factors, ATT stood out as the most potent predictor of behavioral intention. In their, Ateş and Garzón (2023) explored the intentions of science teachers to use Augmented Reality (AR) in their classrooms. To address this, the researchers propose a model that combines the TPB and the Unified Theory of Acceptance and Use of Technology 2. The study tests nine hypotheses through a survey of 451 science teachers from various cities in Turkey. Results suggest that their integrated model provides a more robust framework for understanding the factors influencing teachers' intentions to use AR, outperforming the explanatory power of each theory individually. All the hypotheses were statistically significant, making this study a valuable contribution to both theoretical understanding and practical applications concerning technology adoption in education. Given the demonstrated efficacy of the TPB in shaping educational technology practices within STEM education (Lin & Williams, 2016), and the scarcity of studies specifically focused on this area, our research posits that ATT, SN, and PBC significantly affect teachers' willingness to integrate robotics into STEM education. Accordingly, we hypothesize that:

H11: A higher level of attitude positively correlates with the likelihood of teachers adopting robotics in STEM education.

H12: A higher level of subjective norm positively correlates with the teachers' behavioral intention to adopt robotics in STEM education.

H13: A higher level of perceived behavioral control positively correlates with the teachers' behavioral intention to adopt robotics in STEM education.

The comprehensive unified framework adapted from Ateş and Yılmaz (2023) outlining the relationships among the constructs under study is presented in Fig. 1.

3 Method

3.1 Data collection and participants

The data for this study was garnered using a comprehensive questionnaire survey technique. Prior to participating in the survey, informed consent was obtained from all participants. They were presented with a clear explanation regarding the study's aims, its objectives, and the way their data would be used. Participants were reassured that their participation was voluntary, and they were free to withdraw from the study at any point without any negative repercussions. To uphold the ethical considerations of research, all participants were ensured complete anonymity. No personal identifiers or names were collected in the questionnaire. All data was treated with the strictest confidentiality, stored securely, and only accessible by the research team. The study's intent to protect the identity and responses of the participants was communicated clearly, ensuring their comfort and confidence in their participation.

The convenience sampling strategy was employed for participant selection due to its feasibility and ease of implementation. The questionnaires, designed specifically for this study, were administered in an educational setting, with an estimated time of completion being around 30 min. The lead researcher began the data collection process by outlining the methodology and objectives of the study. Each participant was given an explanatory note regarding the study's aim and was encouraged to read

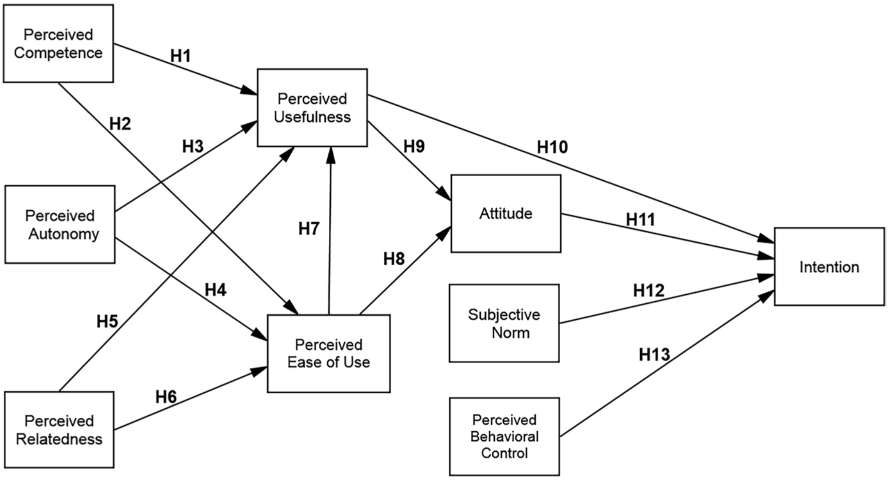

Fig. 1 Unified framework including hypotheses

it diligently. Initially, the study targeted 689 science teachers in Turkey. However, due to various challenges during data processing, such as missing data, apparent carelessness in responses, and potential multicollinearity issues, 84 responses were excluded. This left a total of 605 valid responses. Of these respondents, 340 were females and 265 were males, with ages ranging from 24 to 62 years (M = 39.52, SD = 10.12). This results in an effective participation rate of about 88%, which aligns with accepted survey response standards as cited by Deutskens et al. (2004).

The majority of the participants are employed at public middle schools situated in major Turkish cities, each having populations exceeding one million. These schools are comparable in infrastructure, featuring well-maintained class sizes, state-of-the-art smart boards, and well-equipped science laboratories. The student demographics at these institutions are relatively uniform in terms of economic, familial, and sociocultural backgrounds. On the teacher front, their average professional tenure is 16.42 years. Approximately 68% of these educators are either married or in a committed relationship, and 32% hold advanced degrees, either a master's or a doctorate. Preliminary analysis suggests that while 83% of teachers utilize modern technologies, 58% believe they have the necessary skills for robotics-based STEM teaching. However, only 13% have implemented these methodologies in their courses. This gap between confidence and actual implementation has steered the focus of the study towards understanding teacher intentions. Table 1 indicates the demographic and professional attributes of the teachers surveyed.

3.2 Data collection tools

The design of our questionnaire was a meticulous process, rooted in thorough literature reviews and various validation methods to ensure precision, clarity, and cultural appropriateness. The inception of the survey tool began with an in-depth examination of literature corresponding to the theoretical underpinnings of this study. Drawing from prior studies, preliminary statements were seamlessly integrated into our scales to accurately capture the constructs defined in our conceptual frameworks. To safeguard the instrument's integrity, we ensured both face and content validity. This was crucial to guarantee that our items appropriately reflected their intended constructs, referencing the guidelines by Gravetter and Forzano (2018).

Prior to the final questionnaire rollout, a pilot study was administered to a sample of 189 preservice science teachers. This step was instrumental in gauging the tool's clarity, cultural sensitivity, and readability. Feedback from this phase facilitated essential refinements. Further strengthening our instrument, two subject matter experts – one rooted in science education and the other in computer and instructional technologies – critically evaluated the scales. In light of the target sample consisting of science teachers in Turkey, the questionnaire was initially translated from English to Turkish by a bilingual individual unfamiliar with the study to mitigate potential bias. To further validate the translation, a second bilingual individual back-translated the questionnaire from Turkish to English. This back-translation closely aligned with the original English version, affirming the accuracy of the translation process (Esfandiar et al., 2020).

Table 1 Demographic and professional characteristics of surveyed teachers

Demographic indicator	Frequency	Percentage
Gender		
Female	340	56.2
Male	265	43.8
Age range		
24–30	85	14
31–40	230	38
41–50	200	33.1
51–62	90	14.9
Marital status		
Married/Committed relationship	411	68
Single/Other	194	32
Educational qualification		
Undergraduate	411	67.9
Master	155	25.6
PhD	39	6.4
Professional tenure (years)		
Less than 10	150	24.8
10–20	320	52.9
More than 20	135	22.3
Technology utilization		
Use modern technologies	502	83
Do not use modern technologies	103	17
Robotics-based STEM skills		
Have necessary skills	351	58
Do not have necessary skills	254	42
Robotics in courses		
Implemented	79	13
Not implemented	526	87

The scale developed to assess the role of robotics in STEM education is both comprehensive and multi-faceted, including nine distinct constructs with varying numbers of items to measure each. For instance, PEU and PU each have three items, and both are adapted from seminal work by Davis (1989) along with contemporary research by Ateş and Yılmaz (2023). ATT contains four items and integrates research from Lu et al. (2009) and Taylor and Todd (1995). SN, with its two items, and PBC, with three items, borrow from multiple sources, including Ajzen (2006), Lu et al. (2009), and Taylor and Todd (1995). The constructs of PC, PA, and PR each feature four items and are derived from studies by Baard et al. (2004), McAuley et al. (1989), and Ateş and Yılmaz (2023). Lastly, intention is represented by four items and amalgamates theories from Ajzen (2006), Davis (1989), and Ateş and Yılmaz (2023).

In summary, our research tools consisted of a carefully curated set of 31 items, each designed to uncover the variables affecting science teachers' willingness to incorporate robotics into STEM education. These items were assessed on a 7-point Likert scale, encompassing the spectrum from "strongly disagree" to "strongly agree". A detailed breakdown of constructs, associated items, and their reliability metrics can be found in Table 2.

3.3 Data analysis

In the presented study, both measurement and structural models were rigorously assessed in accordance with Anderson and Gerbing (1988)' suggestions. The measurement model pertained to the reliability and validity assessments of the constructs. Specifically, the confirmatory factor analysis (CFA) was deployed to evaluate the reliability and validity of the suggested model, employing the maximum likelihood estimation technique. The CFA results exhibited an agreeable fit to the acquired data, with statistics $\chi 2 = 687.92$, df = 291; $\chi 2$ /df = 2.36; GFI = 0.92 IFI = 0.93, TLI = 0.90, CFI = 0.94; RMSEA = 0.03; and SRMR = 0.04.

The reliability was assessed using Cronbach's alpha values, following the guidelines by Fornell and Larcker (1981). The Cronbach's alpha values for the constructs ranged between 0.77 and 0.90. These values, surpassing the threshold of 0.70, manifest satisfactory internal consistency reliability as proposed by Hair et al. (2018). In terms of construct validity, it was secured through the paradigms of convergent validity and discriminant validity, which were assessed using parameters including factor loadings (FL), average variance extracted (AVE), and composite reliability (CR), as shown in Table 2. The FL values, which ranged between 0.73 and 0.92, significantly exceeded the recommended benchmark of 0.50 (Hair et al., 2018). The analyses also indicated AVE values between 0.56 and 0.69, surpassing the accepted threshold of 0.5, and the CR values, which ranged from 0.72 to 0.90, were well above the established benchmark of 0.6 as suggested by Bagozzi and Yi (2012). These findings collectively validate the convergent validity of the study's measurement model. As delineated in Table 3, discriminant validity outcomes further revealed that the AVE's square root surpassed all correlations between the constructs.

4 Results

4.1 Goodness of fit and predictive power of unified model

In this study, the theories of TPB, TAM, and SDT were collectively employed to investigate science teachers' intentions regarding the adoption of robotics in STEM education. The constructs of TPB and TAM directly influence intention. Conversely, the constructs of SDT are treated as supplementary variables within the research model, as they have no direct hypothesized correlation with intention.

Table 2 Measurement scales, reliability, and validity metrics for constructs in robotics-integrated STEM education

Constructs	Items	FL	Reliability	AVE	CR	Source
Perceived Ease of Use	I find the robotics technology in STEM education easy to use.	0.71	0.85	0.57	0.80	Davis (1989), Ateş and Yılmaz (2023)
	It is easy for me to become proficient with robotics in STEM education.	0.80				
	My engagement with robotics in STEM education is clear and understandable.	0.75				
Perceived Usefulness	Integrating robotics in STEM education increases my teaching productivity.	0.74	0.89	0.60	0.82	Davis (1989), Ateş and Yılmaz (2023)
	Using robotics in STEM education is useful for my instructional methods.	0.80				
	Incorporating robotics into STEM enhances my overall teaching effectiveness.	0.79				
Attitude	I believe utilizing robotics in STEM education is good idea.	0.81	0.82	0.62	0.87	Lu et al. (2009). Taylor and Todd (1995)
	I like the incorporation of robotics in STEM education.	0.80				
	It seems judicious to use robotics within the STEM curriculum	0.74				
	Engaging with robotics in STEM education feels pleasant.	0.81				
Subjective Norm	People who are important to me think that I should incorporate robotics in STEM education.	0.71	0.77	0.56	0.72	Ajzen (2006), Lu et al. (2009), Taylor and Todd (1995)
	People whose opinions I respect believe I should adopt robotics in my STEM teaching.	0.79				

Table 2 (continued)

Constructs	Items	FL	Reliability	AVE	CR	Source
Perceived Behavioral Control	The decision to use robotics in STEM teaching is fully up to me.	0.80	0.81	0.64	0.84	Lu et al. (2009), Taylor and Todd (1995)
	I have the required skills and knowledge to integrate robotics in STEM education.	0.79				
	I feel confident in using robotics effectively in STEM teaching.	0.81				
Perceived Competence	I consider myself adept at using robotics in STEM education.	0.77	0.79	0.61	0.85	Baard et al. (2004), McAuley et al. (1989), Ateş and Yılmaz (2023)
	Compared to other teachers, I feel proficient in robotics-based STEM teaching.	0.82				
	With experience, I feel highly competent in robotics oriented STEM education.	0.71				
	Robotics in STEM education is an area where I excel.	0.81				
Perceived Autonomy	Robotics-based STEM education offers me a sense of choice and freedom.	0.79	0.84	0.60	0.86	Baard et al. (2004), McAuley et al. (1989), Ateş and Yılmaz (2023)
	I feel pressured when integrating robotics into STEM lessons.	0.77				
	Robotics in STEM education presents me with intriguing options and choices.	0.74				
	There is limited autonomy for me on how to approach robotics in STEM education.	0.79				

Table 2 (continued)

Constructs	Items	FL	Reliability	AVE	CR	Source
Perceived Relatedness	Engaging in robotics-based STEM teaching allows me to connect with fellow educators.	0.81	0.86	0.64	0.88	Baard et al. (2004), McAuley et al. (1989), Ateş and Yılmaz (2023)
	I feel close to peers when I use robotics in STEM education.	0.74				
	Robotics-based STEM education fosters a sense of community among my colleagues.	0.79				
	I feel distant to my colleagues when I participate in the discussions on robotics in STEM.	0.86				
Intention	I foresee myself using robotics in STEM education in the future.	0.81	0.90	0.69	0.90	Ajzen (2006), Davis (1989), Ateş and Yılmaz (2023)
	I am planning to incorporate robotics in my future STEM lessons.	0.89				
	I intend to embed robotics within my STEM teaching going forward.	0.79				
	I am inclined to explore robotics more in upcoming STEM classes.	0.82				

Table 3 Descriptive statistics, validity measures, and correlation values

Constructs	PEU	PU	ATT	SN	PBC	PC	PA	PR	INT
PEU	**0.75**								
PU	0.62	**0.77**							
ATT	0.52	0.42	**0.79**						
SN	0.39	0.31	0.31	**0.75**					
PBC	0.42	0.28	0.39	0.32	**0.80**				
PC	0.38	0.34	0.27	0.34	0.40	**0.78**			
PA	0.32	0.28	0.20	0.34	0.32	0.32	**0.77**		
PR	0.31	0.28	0.31	0.29	0.32	0.34	0.35	**0.80**	
INT	0.30	0.35	0.30	0.39	0.33	0.31	0.26	0.39	**0.83**
M	4.56	4.32	4.78	5.12	4.89	5.13	5.02	4.87	4.63
SD	0.72	0.85	0.94	1.03	0.79	0.88	1.07	0.98	1.08

PEU Perceived Ease of Use, *PU* Perceived Usefulness, *ATT* Attitude, *SN* Subjective Norm, *PBC* Perceived Behavioral Control, *PC* Perceived Competence, *PA* Perceived Autonomy, *PR* Perceived Relatedness, *INT* Intention, *M* Mean, *SD* Standard Deviation. Bold values denote the square of AVE

For model comparison, we gauged the explanatory power of three models: TPB, TAM, and a unified model. SEM results reveal that all models fit well (Bagozzi & Yi, 2012; Browne & Cudeck, 1993). However, when comparing the models, the unified model demonstrated superior fit ($\chi2/\mathrm{df}=2.57$) over TPB ($\chi2/\mathrm{df}=2.65$) and TAM ($\chi2/\mathrm{df}=2.71$). Furthermore, the unified model indicated enhanced explanatory power ($R^2=0.48$) in contrast to TPB ($R^2=0.43$) and TAM ($R^2=0.38$). Detailed outcomes can be found in Table 4.

4.2 Hypothesis testing results

The findings from the structural model, as illustrated in Fig. 2; Table 5, reveal several significant relationships. Firstly, PC ($\beta=0.31$), PA ($\beta=0.21$), and PR ($\beta=0.30$) demonstrated significant positive associations with PEU. Concurrently, these constructs displayed positive correlations with PU ($\beta_{PC}=0.25$; $\beta_{PA}=0.39$; $\beta_{PR}=0.27$). This evidence substantiates hypotheses H1 through H6. In the realm of TAM constructs, PEU was observed to notably influence PU ($\beta=0.43$) and the ATT towards the utilization of robotics in STEM education ($\beta=0.39$). Furthermore, significant associations were discerned between PU and both ATT ($\beta=0.38$) and the intention

Table 4 Results of goodness of fit and predictive powers

	χ^2	df	χ^2/df	GFI	IFI	TLI	CFI	RMSEA	SRMR	R^2
TPB	441.78	167	2.65	0,92	0.92	0.93	0.94	0.53	0.49	0.43
TAM	498.12	184	2.71	0.92	0.91	0.92	0.96	0.57	0.54	0.38
Unified model	657.12	256	2.57	0.93	0.93	0.94	0.95	0.41	0.39	0.48

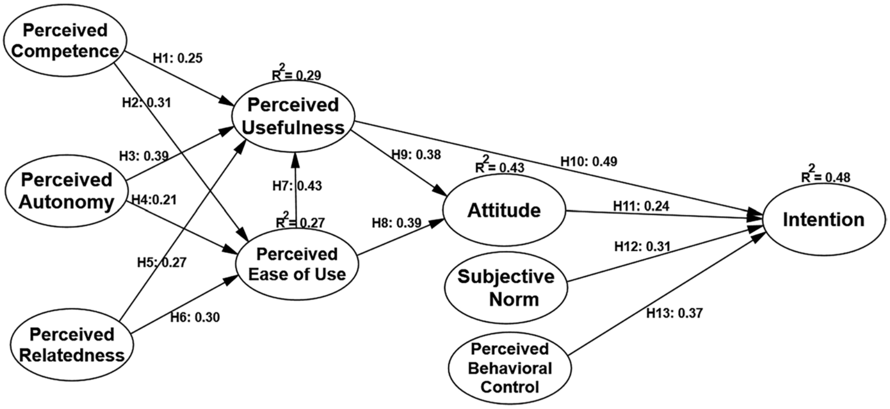

Fig. 2 Results of the unified model

Table 5 SEM results of the unified framework

Hypothesis	Relationship	Beta coefficient (β)	t-value	Hypothesis Situation
H1	$PC \rightarrow PU$	0.25**	5.47	Confirmed
H2	$PC \rightarrow PEU$	0.31**	6.8	Confirmed
H3	$PA \rightarrow PU$	0.39***	8.87	Confirmed
H4	$PA \rightarrow PEU$	0.21**	4.65	Confirmed
H5	$PR \rightarrow PU$	0.27**	6.03	Confirmed
H6	$PR \rightarrow PUE$	0.30**	6.55	Confirmed
H7	$PEOU \rightarrow PU$	0.43***	10.07	Confirmed
H8	$PEOU \rightarrow ATT$	0.39***	8.65	Confirmed
H9	$PU \rightarrow ATT$	0.38***	8.01	Confirmed
H10	$PU \rightarrow INT$	0.49***	11.47	Confirmed
H11	$ATT \rightarrow INT$	0.24**	5.22	Confirmed
H12	$SN \rightarrow INT$	0.31**	6.98	Confirmed
H13	$PBC \rightarrow INT$	0.37***	7.74	Confirmed
Variance explained:	Indirect effect:			
R^2 $(PU) = 0.29$	$\beta PEOU \rightarrow ATT = 0.35 **$ $\beta PR \rightarrow ATT = 0.27 *$			
R^2 $(PEU) = 0.27$	$\beta PEOU \rightarrow INT = 0.29 **$ βPC→INT = 0.20*			
R^2 $(ATT) = 0.43$	$\beta PU \rightarrow ATT = 0.25 *$ βPA→INT=0.22*			
R^2 $(INT) = 0.48$	$\beta PC \rightarrow ATT = 0.27 *$ βPR→INT=0.29**			
	$\beta PA \rightarrow ATT = 0.15 *$			

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

to integrate robotics into STEM education (β = 0.49). These results lend credence to hypotheses H7 through H10. In the concluding observations, ATT (β = 0.24), SN (β = 0.31), and PBC (β = 0.37) emerged as strong predictors of the intention to adopt robotics in STEM classrooms, thus supporting hypotheses H11, H12, and H13. From an explained variance perspective, the constructs PC, PA, PR, and PEU accounted for roughly 29% of the total variance in PU. Separately, the constructs PC, PA, and

PR were responsible for an approximate 27% of the variance in PEU. Moreover, a combined 43% of the variance in ATT was attributable to PEU and PU. In the ultimate analysis, the constructs from TPB, namely ATT, SN, and PBC, explained an estimated 48% of the variance in intention. Regarding mediating effect, the SEM findings underscore several noteworthy indirect effects. Specifically, PEU (β = 0.35) demonstrated an influence on ATT mediated by PU. Notably, both PU (β = 0.25) and PEU (β = 0.29) exhibited a significant mediating effect on intention via ATT. Delving deeper into the effects, PC (β = 0.27), PA (β = 0.15), and PR (β = 0.27) were found to indirectly influence ATT, with PU and PEU serving as mediating variables. In the final observations, PC (β = 0.20), PA (β = 0.22), and PR (β = 0.29) displayed significant indirect relationships with intention, mediated through PU.

5 Discussion and implications

5.1 Summary of the results

The current research integrated SDT, TPB, and TAM into a unified framework to understand the intentions of science teachers to adopt robotics in STEM education. The theoretical associations were determined to be significant, with PU, PEU, and ATT playing crucial mediating roles. These findings offer substantial insights into the educational technology literature concerning science teachers' intentions to incorporate robotics in STEM teaching, highlighting individual, social, and motivational facets. Ultimately, the insights from this research can guide the development of effective strategies to aid science teachers in enhancing their proficiency in robotics-centric STEM educational initiatives.

5.2 Theoretical implications

The current research offers both theoretical and empirical insights into the determinants influencing science teachers' intentions to adopt robotics in STEM education. To the best of our understanding, this is a pioneering effort to amalgamate three prominent theoretical frameworks – SDT, TPB, and TAM – to decipher the motivations behind science teachers' adoption behaviors. Historically, SDT has been ratified in numerous studies, underscoring both intrinsic and extrinsic motivational factors pertaining to educators (Chiu, 2022; Liu et al., 2022; Xia et al., 2022). Concurrently, TPB has been implemented across diverse landscapes, encompassing science teachers' digital learning tendencies (Al Breiki et al., 2023; Ateş & Garzón, 2023). TAM, a foundational model in this domain, has consistently been leveraged to unravel teachers' e-learning propensities (Almaiah et al., 2022; Khong et al., 2023). In this endeavor, we articulated a theoretical framework, amalgamating the strengths of SDT, TPB, and TAM, to delineate the underpinnings of science teachers' proclivities towards robotics integration in STEM classrooms. The interrelationships among the pivotal constructs from these models were carefully assessed, culminating in a cohesive conceptual structure. The empirical findings from this study corroborated the constructed theoretical model, painting it as a comprehensive representation of science teachers adoptions on robotics-based in STEM education. This has profound ramifications, spotlighting the intricate interplay of motivational, societal, and individual determinants in shaping the technology adoption trajectory among science educators.

The findings of this research reveal that by merging the foundational constructs of SDT, TPB, and TAM, an impressive 48% of the variance in science teachers' intentions to incorporate robotics in STEM education can be explained. This outperforms the individual explanations provided by TPB (43%) and TAM (38%). Such a result underscores the efficacy of harnessing the synergistic power of these three theoretical models, as opposed to relying solely on TPB or TAM. Furthermore, within the context of robotics in STEM education, the study indicated a slight preference for TPB's explanatory power over that of TAM. This emphasizes the pivotal role of non-volitional factors, especially when navigating the intricacies of digital learning platforms. Contrary to focusing solely on science teachers' adoption of robotics-based STEM education, our study stands out by synthesizing motivational, volitional, and non-volitional aspects into a singular, holistic model tailored for STEM educators' adoption regarding robotics.

The findings from this study align with earlier comparative research in the educational technology field that also focus on TPB and TAM, as evidenced by works such as those by Ateş and Garzón (2022); Wang et al. (2022a, b). Delving into the relative importance of SDT constructs, as hypothesized from H1 to H6, it became evident that the components PC, PA, and PR exert influence on PU and PEU, elucidating 29% and 27% of the variance respectively. These results suggest a correlation between science teachers' confidence in utilizing robotics in STEM education and their belief in its potential to enhance pedagogical efficacy. Analogously, a teacher's autonomy in decision-making related to robotics integration and their interpersonal relations within the academic milieu positively inform their perceptions regarding the ease of use and utility of robotics. These results also imply that fostering teacher confidence, endorsing autonomy, and nurturing professional relationships can amplify educational effectiveness. Pioneers in this domain, such as Deci et al. (1989) and Williams et al. (1996), have accentuated the pivotal role intrinsic motivation plays in achieving elevated outcomes.

This study emboldens the discourse by underscoring the pivotal influence of SDT constructs on PU and PEU. While its conclusions align with several prior investigations like those of Tsai et al. (2021), they also diverge from a substantial number of others, such as Rosli and Saleh (2022), and Sørebø et al. (2009). In the Sørebø et al. (2009)' study, it was deduced that teachers' intrinsic motivations and interconnectedness with esteemed peers don't necessarily forecast their belief in a technological tool's capacity to enhance professional efficiency. A more recent inquiry by Racero et al. (2020) negated any substantial relationship between PC, PU, and PEU. In sum, though divergent narratives exist within the academic community, the current study firmly establishes the relevance and applicability of SDT in deciphering science teachers' perceptions of robotics within STEM education concerning its perceived ease and value. The findings associated with TAM bolstered hypotheses from H7 to H11, elucidating that the PEU profoundly influenced both PU and teachers'

ATT. Significantly, PU was found to correlate robustly with teachers' ATT and their intention to incorporate robotics in STEM education. In a notable revelation, PU and PEU collectively accounted for 43% of the variance in teachers' ATT toward employing robotics within their STEM curriculum. This underscores the profound theoretical implication that the constructs embedded within TAM are instrumental in shaping the dynamics. The findings attest that the accessibility and tangible benefits of using robotics in STEM education are pivotal in fostering favorable dispositions and proactive intentions among science teachers. This aligns harmoniously with the research conducted by Sungur Gül and Ateş (2022), where it was delineated that when educational tools in STEM education are perceived as both accessible and beneficial, educators are more inclined to integrate it into their pedagogical repertoire. Examining the constructs within TPB, specifically H12 and H13, it emerged that SN and PBC wield a noteworthy positive impact on the intention to integrate robotics. This resonates with the insights from Lin and Williams (2016), accentuating the influential role of societal expectations on educators' predilection toward STEM education. Additionally, the ease or complexity perceived in the adoption of such technologies plays a quintessential role in shaping decisions.

PU, PEU, and ATT emerged as pivotal mediators in elucidating science teachers' intentions to adopt robotics within the realm of STEM education. These constructs, which bridge the frameworks of SDT, TPB, and TAM, inject substantial theoretical depth to the current investigation. Such findings align with prior studies that amalgamated distinct theoretical models to test mediating effects, especially in technology-enhanced learning environments (e.g., Ateş & Yılmaz, 2023; Lee et al., 2023; Wang et al., 2022a, b). Taking into account the mediating functions of these constructs, the results underscore the efficacy of employing these variables as mediators when refining or expanding an existing model and formulating a novel one.

5.3 Practical implications

From a practical perspective, the study on the adoption of robotics by science teachers in STEM education offers comprehensive insights, implicating a diverse array of stakeholders including policymakers, teacher educators, school administrators, curriculum developers, IT departments, the tech industry, and educators across disciplines.

To begin with,, the study accentuates the correlation between science teachers' affirmative perceptions of using robotics in STEM education and their propensity to integrate it into their teaching methodologies. Hence, beyond policymakers and school administrators, curriculum developers and instructional designers should be alerted to this nexus. They should consider curating content and instructional strategies that resonate with the potential and dynamism of robotics. School administrators, specifically, should spearhead initiatives that bolster teachers' positive outlook towards this integration, such as piloting technology-driven lessons, allocating funds for robotic kits, and promoting R&D initiatives specific to STEM and robotics. Furthermore, the study shows that how useful, easy to use, and the overall ATT towards robotics strongly influence teachers' interest in using it. This suggests that teacher training centers and those who provide professional development should offer clear, hands-on training about robotics. This training can help teachers see the benefits of robotics and make them more comfortable with using it. Additionally, to practically embed robotics in classrooms, logistics and infrastructure play a pivotal role. This underscores the role of school management and IT departments, who can ensure the seamless integration of robotics by provisioning the requisite hardware, software, and connectivity. Moreover, continuous training should be a mainstay to keep educators abreast of the ever-evolving robotic technologies. Moreover, in consideration of the diversity in the level of technology adaptability among teachers, a tiered approach towards professional development can be implemented. Beginner, intermediate, and advanced modules can cater to teachers based on their pre-existing robotics knowledge, ensuring that the training is relevant, engaging, and progressively challenging. Beyond the walls of the educational institutions, tech industry stakeholders can forge collaborations with schools to co-create customized robotics modules that are in sync with the curriculum, enhancing the practical relevance and applicability of robotics in the STEM classroom. Such collaborations can pave the way for periodic industry-led workshops, ensuring that the knowledge imparted is contemporaneous and industry-aligned. Another pivotal practical implication revolves around feedback mechanisms. Schools should institutionalize a system wherein teachers can regularly share their on-ground experiences, challenges, and success stories related to robotics adoption. This not only fosters a culture of shared learning but also aids administrators and policymakers in making informed decisions about future investments in technology and training. In addition, the significant influence of societal expectations on educators' inclination to adopt robotics underscores the importance of fostering a positive societal narrative around STEM and robotics education. Engaging parents and the larger community through informational sessions, workshops, and open houses can be a catalyst in molding a supportive environment, propelling teachers to be more open and enthusiastic about integrating robotics. Lastly, while the study underscores the significance of intrinsic motivation factors such as perceived confidence, autonomy, and interpersonal relationships in the academic milieu, practical strategies should be devised to cultivate these. Mentorship programs, where seasoned educators guide the newer ones in their robotics journey, can be beneficial. Such initiatives not only elevate the confidence levels of educators but also foster a collaborative spirit, promoting the ethos of shared growth and learning.

5.4 Limitations and future studies

The present research, akin to all empirical endeavors, possesses inherent limitations which, in turn, offer opportunities for subsequent investigations. One significant limitation lies in the demographic focus, as this study centered exclusively on science teachers' adoption of robotics in STEM education. While this specificity undeniably adds depth to our findings, it concurrently hampers the breadth of generalizability across other academic subjects or distinct educational strata. Hence, future research could elevate the discourse by embracing a more expansive scope that encapsulates educators from an array of disciplines or diverse educational contexts. Geographically, the confinement of this study to a particular region or country (a supposition rooted in typical research constructs) introduces another layer of limitation. Given the intrinsic disparities in cultural, economic, and educational paradigms across the globe, it becomes crucial to acknowledge that the current findings might resist universal applicability. An intriguing avenue for subsequent studies, therefore, lies in adopting a cross-cultural or even an international lens. Such an approach could be instrumental in discerning whether the insights derived are emblematic of universal pedagogical trends or are shaped by regional idiosyncrasies.

6 Conclusion

In this study, we advance beyond current frameworks by innovatively combining elements of TAM, TPB, and SDT—a synthesis notably absent from existing literature. Our proposed theoretical model, featuring nine constructs and 13 causal relationships, received robust empirical support. We were able to successfully achieve all four research objectives and identify significant mediating roles for certain variables within the model. Reflecting upon the existing literature, our findings exhibit both convergences and divergences. In terms of alignment, our study corroborates the prevailing belief in the literature regarding the influence of perceived usefulness and ease of use in determining technology adoption. Additionally, the significance of intrinsic motivational factors echoes earlier studies, reinforcing their importance in the adoption process. However, the stark differentiation lies in our combined use of TAM, TPB, and SDT. While each framework has been individually explored in prior studies, the synthesis and interplay of constructs from all three in a singular model is a pioneering effort. This amalgamation reveals intricate nuances and interrelationships that were previously overlooked or underemphasized. While there has been limited effort to date in amalgamating TAM, TPB, and SDT into a single framework, this research offers substantial and original contributions to this nascent area of inquiry. Moreover, the study enriches the broader literature on STEM education and educational technology. It provides educators, tech designers, and administrators with clear ways to improve the role of robotics in teaching. Our findings set the stage for a more effective and innovative teaching approach, positioning robotics at the heart of the learning experience.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical considerations but are available from the corresponding author on reasonable request and subject to necessary approvals.

Declarations

Conflict of interest The authors declare no conflict of interest.

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