The affordances of artificial intelligence-based tools for supporting 21st-century skills: A systematic review of empirical research in higher education

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Twenty-first-century skills should be integrated into higher education to prepare students for complex working-life challenges. Artificial intelligence (AI)-powered tools have the potential to optimise skill development among higher education students. Therefore, it is important to conceptualise relevant affordances of AI systems for 21st-century skills development in higher education. This study aimed to present an overview of journal articles published in the Web of Science database that specifically addressed the affordances of AI-based tools for 21st-century skills development. Four distinct categories of AI-based tools (intelligent tutoring systems, chatbots, AI-powered dashboards and automated grading systems) were identified as capable of promoting six main 21st-century skills (collaboration, communication, creativity, critical thinking, information and communication technology and problem-solving). The review revealed that the utilisation of AI-based tools might contribute to the simultaneous development of multiple 21st-century skills (e.g., collaboration and critical thinking). The results showed that adaptive feedback from AI plays a significant role as a facilitator in the development of 21st-century skills. Furthermore, the utilisation of diverse functional AI affordances (e.g., prediction and profiling) might contribute to the development of various skills. AI-based technologies appeared to target the 21st-century skills of problem-solving and its subskills the most.

Implications for practice or policy:

- More functional affordances of AI (e.g., prediction and profiling) should be employed in AI-based tools. This could support higher education students' 21st-century skills.
- AI-based tools (e.g., chatbots and intelligent tutors) interact with end users through their data. AI systems have the potential to promote 21st-century skills by using students' multimodal data.
- AI technologies should be more integrated into the social sciences and humanities in the higher education context to support students' 21st-century skills.

Keywords: artificial intelligence, intelligent systems, 21st-century skills, higher education, systematic review

Introduction

In order to face demanding and competitive working-life challenges, today's higher education students need to develop various knowledge and skills. Overcoming such challenges requires more than being a knowledgeable employee in a specific field (e.g., business or health): individuals should also know how to collaborate in tough situations and solve problems by managing unexpected conflicts (Rios et al., 2020). In these situations, they might come up with creative solutions after searching for relevant information on the Internet. Individuals should approach Internet-based information critically and constantly justify it for their problem-solving (Van Laar et al., 2017). Therefore, in their future professional lives, higher education students might need general and transferable skills, such as problem-solving, creative thinking and collaboration, which are defined as 21st-century skills (Muukkonen et al., 2022; Van Laar et al., 2020).

Higher education is a crucial context in which students can be empowered with 21st-century skills. In order to achieve this, instructional pedagogy to support skills such as collaborative problem-solving can be implemented in higher education courses (Hämäläinen et al., 2017). Instructional technologies could also help students gain 21st-century skills (Benvenuti et al., 2023; T. Wang et al., 2023). In fact, emerging

technologies such as artificial intelligence (AI)-powered tools have the potential to optimise skill development among higher education students (Benvenuti et al., 2023; Gedrimiene et al., 2023). For instance, due to time limitations, many instructors fail to provide adaptive and immediate feedback in response to students' questions during their problem-solving tasks (L. Chen et al., 2020). Chatbots – a prevalent AI technology – could be used to answer student inquiries, facilitating them in gaining problem-solving skills (L. Chen et al., 2020). Hence, it is crucial to conceptualise the relevant affordances of certain AI systems for 21st-century skills development in the higher education context. A systematic review of empirical research might help with this conceptualisation. However, none of the systematic reviews conducted to date have focused on the functional affordances of AI-based technologies for 21st-century skills from a holistic perspective. Understanding the affordances and challenges of using AI systems to contribute to 21st-century skills would be beneficial for technology developers and educators.

The rest of this paper is structured as follows. First, the theoretical framework is presented in three sections: (a) 21st-century skills, (b) affordance theory and (c) AI and its affordances for supporting 21st-century skills. Second, the purpose of the review and the methodological approach are explained. Third, a synthesis of the reviewed articles is presented and discussed in detail. Fourth, a discussion of the main findings is provided and concluding remarks are made.

Theoretical framework

Twenty-first-century skills

Skill is defined as the ability to use knowledge effectively in the execution of a task. It is a learned ability to do something competently (Griffin & Care, 2014). Today, being successful and productive requires individuals to adapt to rapidly changing societal contexts, for example, education and the workplace (Van Laar et al., 2020). Such adaptation necessitates the development of a range of knowledge and skills in addition to domain-specific competencies (Binkley et al., 2012). These skills are coined as 21st-century skills.

Several frameworks that define 21st-century skills have been developed in recent years. Examples of these frameworks are the partnership for 21st century skills (Battelle for Kids, 2024), also known as the 4C framework (collaboration, communication, critical thinking and creativity), and the assessment and teaching of 21st century skills (Griffin & Care, 2014). To date, researchers have not reached consensus on which skills constitute 21st-century skills. For instance, some regard computational thinking as one of the 21st-century skills, extending 4C to 5C with the addition of computational thinking (Grover & Pea, 2013). However, computational thinking is seen as a form of problem-solving in other frameworks (Yadav et al., 2016). Furthermore, Fishman et al. (2016) stated that problem-finding is also an important skill as a problem cannot be solved until it has been identified. Voogt and Roblin (2012) claimed that all frameworks include information and communication technology (ICT)-related skills, collaboration, and communication. Additionally, creativity, critical thinking, and problem-solving are reported as key 21st-century skills in many studies (Van Laar et al., 2020). In this study, we addressed six main 21st-century skills: communication, collaboration, ICT skills, creativity, critical thinking and problem-solving. We follow an analytical and detailed approach to better understand the role of AI technologies in promoting 21st-century skills. In particular, subskills associated with key skills are also investigated. Instead of dealing with 21st-century skills by using a single framework, we analysed and interpreted six skills based on various frameworks: the knowledge, skills, attitudes, values and ethics framework (KSAVE) (Binkley et al., 2012), the core 21st-century skills framework (Van Laar et al., 2017) and the complex problem-solving framework (Fischer et al., 2011). Table 1 shows the six key skills and associated frameworks addressed in this review.

According to these frameworks, communication skills include the ability to speak, write and listen in one's mother tongue and additional languages. Collaboration is defined as the ability to interact effectively with others and work in different teams. A person with strong collaboration skills can manage project activities by guiding and leading others (Binkley et al., 2012). Creativity is a way of thinking that leads to innovative

ideas. Creative people are able to work with others to apply unique thoughts. ICT skills refer to the ability to access and evaluate information effectively and create media content (Binkley et al., 2012).

Table 1
Twenty-first-century skills and guiding frameworks

Skills	Frameworks	Authors
Collaboration skills Communication skills Creativity skills ICT skills	KSAVE	Binkley et al. (2012)
Critical thinking skills	Core skills	Van Laar et al. (2017)
Problem-solving skills	Complex problem-solving framework	Fischer et al. (2011)

People who are competent in ICT are capable of using and applying several technologies. When people think critically, they classify and link various ideas by constantly assessing and justifying them (Van Laar et al., 2017). Problem-solving skills are conceptualised as the ability to understand a problem and gather relevant information about it. Individuals with these skills can effectively define the available resources and what is needed to solve problems. Such people plan their steps before problem-solving and manage themselves in response to cognitive and emotional challenges in the problem-solving process (Fischer et al., 2011).

As the above description of skills suggests, such skills are necessary in the 21st century and will remain necessary in the centuries to come. In other words, we see these six skills (collaboration, communication, creativity, ICT, critical thinking and problem-solving) as independent from a certain period of time. Thus, in this review, 21st-century skills are tackled as an umbrella term highlighting crucial core skills for higher education students in this century and in future ones. For example, collaboration is perceived as a perennial requirement of workplaces across the centuries (Van Laar et al., 2017). Therefore, the fundamental value of collaboration is not unique to the 21st-century economic context (Dede, 2010). However, the significance of collaboration is rising in the current era as knowledge-based economies gather momentum. This is because work tasks are accomplished by teams of individuals with differing expertise and knowledge (Dede, 2010). This collaborative working style contrasts the isolated way in which individuals generally work in industrial settings (Wu et al., 2023). As a result, economic conditions in future centuries are likely to require more collaboration among individuals. We argue that higher education institutions serve to prepare students to develop crucial skills for future economies. In this preparation process, the affordances of AI-based technologies could be used to support skill development.

Affordance theory

According to Gibson (1977), the affordance concept is associated with the action possibilities of a certain object. From a human–computer interaction perspective, individuals initially develop an understanding of perceptual affordances of technologies when engaging with them; ultimately, individuals benefit from these identified affordances by putting them to practical use (Mettler & Wulf, 2019). Researchers have utilised affordance theory to better understand the interactions between tangible technologies and individuals' usage of these technologies (Parchoma, 2014) by describing possible outcomes of technology usage. For instance, Fu et al. (2020) identified four key affordances of AI-based automated grading applications from an end user's perspective. They found that speech recognition, social presence, peer influence and timely feedback are major affordances of automated grading systems that promote continuous intention to learn. Similarly, Moussawi (2018) empirically reported the affordances of chatbots in everyday life, showing that end users find emotional connection, interaction,and personalisation to be crucial factors for effectively using chatbots. Hartson (2003) suggested using the functional affordances concept to further analyse the benefits of any object or technology. Functional affordances have a strong connection to both the usefulness of a technology and the user experience; thereby, functional affordances have a considerable impact on how users interact with a technology and

comprehend it (Hartson, 2003). This study reviewed articles on the user experience of AI-based tools. Therefore, we reviewed the functional affordances of AI-based tools associated with 21st-century skills.

AI and its affordances for supporting 21st-century skills

AI as a technical and umbrella term refers to a technology that is capable of executing a task attributed to humans by reasoning and engaging with the environment (Zawacki-Richter et al., 2019). In this regard, a technology enhanced by AI could capture data from its environment, automatically analyse it and generate customised and environment-related outputs. AI covers a set of analytical methods and subfields. Among these subfields, machine learning, natural language processing and deep learning are pervasive (Celik, 2023a; Celik et al., 2022). Machine learning uses data and algorithms to imitate how humans learn by gradually improving accuracy (Pillai & Tedesco, 2023). Natural language processing enables a computer to understand text and spoken words in a way that is similar to how human beings understand them (Pillai & Tedesco, 2023). Deep learning is a sophisticated form of machine learning that processes huge amounts of data to perform automation and achieve tasks without human intervention (Pillai & Tedesco, 2023).

In learning and teaching settings, several tools are powered with AI to achieve various purposes (Gedrimiene et al., 2024). Our review focused on four distinct AI technologies: chatbots, intelligent tutoring systems, AI-based dashboards and automated grading applications. We selected these tools since studies have reported them as the most widespread intelligent technologies for educational purposes (Akgun & Greenhow, 2021; X. Chen et al., 2022).

Chatbots are mainly operationalised by natural language processing. They serve as conversational agents that simulate human conversation by creating automated responses (Luo et al., 2019). During the learning process, students can initiate conversations with chatbots through voice or text inputs (Chocarro et al., 2023; Luo et al., 2019). Today, chatbots are commonly used as language partners for practising foreign languages, which is a subskill of communication. Hence, the use of chatbots might be beneficial for gaining 21st-century skills (e.g., collaboration and communication).

Intelligent tutoring systems are also known as adaptive learning platforms and personalised learning systems. They provide students with learning material in response to their needs (Pai et al., 2021). Students' data are used to define students' personalised needs (Azevedo et al., 2022). Through the functions of classification or prediction from machine learning algorithms, learning content is matched with student-specific needs. This provides opportunities for considering student readiness in defining the difficulty level of problems in problem-solving processes. Hence, giving each student ideal problems to solve could enhance their problem-solving skills (T. Wang et al., 2023).

AI dashboards are mainly utilised to visualise the data gathered from end users (Pardo et al., 2018). In order to produce timely and adaptive visualisations, they are powered by pattern recognition and artificial neural networks (Gobert et al., 2023). Visualisations from AI dashboards could be used to monitor students' collaboration in online learning (Echeverria et al., 2023) and to make team members aware of their strengths and weaknesses when they plan further activities (Gobert et al., 2023; Pardo et al., 2018). Therefore, AI-enhanced dashboards could play a useful role in the development of collaboration skills.

Automated grading applications are interchangeably used with automated assessment systems. The AI subfields of natural language processing and automated speech recognition are commonly employed for automation functions (Ahn & Lee, 2016). These systems capture responses from students and automatically score them based on certain criteria (X. Chen et al., 2022). In a complex writing assignment, automated grading applications may support students' efforts to clarify their responses and link their argumentation, contributing to students' critical thinking skills (Geigle et al., 2016).

The purpose of the study

It is important to review empirical research on how AI can contribute to 21st-century skills since this would reveal the current state of the art in the field (Davies et al., 2010). In this way, the review process might reveal literature gaps and provide guidance for researchers, who can formulate their research aims to fill these gaps. The synthesis of systematic reviews is also important for policymakers and administrators, who must define essential strategies regarding AI and higher education (Hwang & Tsai, 2011).

Since AI and its implications have been popular research topics recently, researchers have conducted systematic literature reviews on the scope of AI in education. These have focused on topics such as the advantages and challenges of AI for K-12 teachers (Celik et al., 2022), the implications of AI applications in higher education (Zawacki-Richter et al., 2019), AI and its ethical challenges (Akgun & Greenhow, 2022) and the administrative role of AI in education (Ahmad et al., 2022). However, there is a dearth of review studies on AI and 21st-century skills (e.g., Benvenuti et al., 2023), and reviews have not addressed the functional affordances of AI for skill development at the higher education level. In order to fill these gaps in the literature, this study presents an overview of all relevant journal articles addressesing AI-based tools and 21st-century skills and published in the Web of Science (WoS) database. More specifically, the purpose of this study was to provide a conceptualisation of the functional affordances and challenges of AI-based tools in fostering 21st-century skills. Since the interaction between AI-based tools and students takes place by means of data, we also reviewed the data modalities collected from students in the articles. The following research questions (RQs) were addressed:

(1) What is the distribution of 21st-century skills supported by AI-based tools?
(2) What is the distribution of AI-based tools over the studies conducted to support 21st-century skills?
(3) What data modalities were gathered from participants in the empirical studies on AI-based tools and 21st-century skills?
(4) What are the functional affordances of AI-based tools for supporting 21st-century skills?
(5) What are the challenges of AI-based tools in supporting 21st-century skills?
(6) What is the distribution of learning and teaching domains in which AI-based tools were integrated to support 21st-century skills?

Method

A systematic literature review was conducted to organise all eligible scientific reports that met predetermined relevant criteria to provide an overview of the topic of interest (Shamseer et al., 2015). This study was guided by the preferred reporting items for systematic reviews and meta-analyses process (Moher et al., 2015), a step-by-step methodological approach that guides researchers in the identification, selection and analysis of studies. Specifically, we reviewed empirical articles addressing AI-based tools and 21st-century skills in the higher education context.

The manuscript selection process

Since it is not possible to incorporate all related studies in literature reviews, researchers have used various methods to select relevant manuscripts (Heitink et al., 2016). For instance, studies have been selected from Social Sciences Citation Index indexed journals (Akçayır & Akçayır, 2018) or certain databases, such as ProQuest (Drysdale et al., 2013) or the Education Resources Information Center (Kucuk et al., 2013). For this review, the WoS database was used to select scientific articles on AI-based tools and 21st-century skills that were published in Social Sciences Citation Index, Emerging Sources Citation Index and Science Citation Index Expanded indexed journals. The WoS database includes leading journals with high impact factors, and articles in such journals are among the top-cited research (Chu et al., 2022).

The selected search terms were implemented using the advanced search function in the WoS. Table 2 shows the search terms used and the main research concepts linked to them. We utilised the Boolean

operator "OR" to combine various search terms that are used interchangeably (e.g., chatbots and conversational agents). In addition, the AND function was used to narrow the research topic (e.g., AI-based tools and higher education).

Table 2
Research concepts and their related search terms

Research concepts	Search terms
AI	"artificial intelligence" OR "machine intelligence" OR "intelligent support" OR "intelligent virtual reality" OR "chatbot*" OR "automated tutor" OR "personal tutor*" OR "intelligent agent*" OR "expert system" OR "AI-based" OR "automated grad*" OR "automated scor*"
Twenty-first-century skills	"twenty-first century skills" OR "21st-century skills" OR "collaboration" OR "critical" OR "creativity" OR "communication" OR "problem-solving" OR "collaborativ*" OR "teamwork*" OR "creativ*" OR "critical thinking" OR "problem-solving" OR "digital skills" OR "digital competenc*" OR "digital literac*" OR "ICT skills" OR "ICT competenc*" OR "ICT literac*"
Higher education	"higher education" OR "college" OR "undergrad" OR "graduate" OR "postgrad*"

For this review, we selected articles written in English that were published between 1 January 2014 and 20 April 2023. The initial search yielded 274 articles, which were screened based on the inclusion and exclusion criteria shown in Table 3. In addition, we read the titles, abstracts and methods sections of all articles to check whether their scope and results were consistent with the aims of this review. A total of 37 empirical articles were assessed as suitable for achieving the aims of this review.

Table 3
Inclusion and exclusion criteria for screening

Inclusion criteria	Exclusion criteria
User engagement with AI-based tools	No user engagement with AI-based tools
Dealing with 21st-century skills (collaboration, communication, creativity, problem-solving, critical thinking, ICT skills)	Not related to any 21st-century skills (collaboration, communication, problem-solving, critical thinking, ICT skills)
Higher education context	Not higher education context (e.g., K-12)
Published from 1 January 2014 to 20 April 2023	Published before 2014
Empirical or primary research	Not primary research (e.g., review)
Presence of at least one AI-based tool (e.g., chatbot)	Absence of any AI-based tool

The data coding and analysis processes

We read and coded the content of the articles separately. In order to answer RQ1, we coded 21st-century skills associated with AI-based tools based on three different frameworks: KSAVE (Binkley et al., 2012), core 21st-century digital skills (Van Laar et al., 2017) and the complex problem-solving framework (Fischer et al., 2011). Communication skills were addressed using two subskills: (a) competency in the mother tongue and (b) competency in additional languages. Collaboration skills were assessed using two subskills: (a) interact effectively with others, (b) work effectively in diverse teams, (c) manage projects and (d) guide and lead others. Creativity skills were tackled using three subskills: (a) think creatively, (b) work creatively with others and (c) implement innovations. ICT skills consisted of four subskills: (a) access and evaluate ICT, (b) use and manage information, (c) create media products and (d) apply technology effectively. We coded critical thinking skills using two subskills: (a) clarification and/or linking ideas and (b) assessment and/or justification. Problem-solving was handled using four subskills: (a) information retrieval and integration, (b) goal elaboration and balancing, (c) action planning and decision-making and (d) self-management. In order to answer RQ2, we coded the articles by focusing on four AI-based tools – chatbots, AI-based dashboards, automated grading systems and intelligent tutoring systems – which are reported as the most widely used (Akgun & Greenhow, 2022; Celik, 2023b). In order to classify data modalities

(RQ3), we determined six data modalities from studies on multimodal data analytics (e.g., Noroozi et al., 2020): video, self-reported (questionnaires, surveys), text (or discourse), user queries (input), performance test and audio. Similarly, in order to code the advantages and challenges of AI-based tools for 21st-century skills (RQ4 and RQ5), we used AI reviews in education (Celik et al., 2022; Zawacki-Richter et al., 2019). The advantages were coded into seven categories: prediction, profiling, recommendation, adaptive feedback, automated assessment, engagement and monitoring. The challenges were revealed through the following: accuracy of assessment, provision of personalised learning content, time limit, technical capacity, autonomy of decision and number of data modalities. The departments in which the participants studied were noted to understand the distribution of learning and teaching domains (RQ6). The investigator triangulation approach was employed to ensure the coding reliability of the analysis (Denzin, 2017). That is, we coded half of the articles (n = 19) separately and then shared the code list and sample studies representing the relevant codes. After the coding of the remaining articles (n = 18) was completed, we negotiated disagreements. In this stage, we checked the coding scheme and the relevant articles by discussing the most suitable categories. As a result, some articles were re-coded or evaluated in terms of multiple skills.

Limitations

Although we conducted this systematic review rigorously, each review has limitations. The first limitation is the relationship between AI technologies and 21st-century skills. We reviewed empirical articles that used cross-sectional methodologies. In these studies, researchers reported which 21st-century skills were targeted and how AI-based tools might support these skills. However, it is necessary to employ an experimental methodology to determine the actual effect of AI-based tools on 21st-century skills. Therefore, our results from the review should be interpreted as highlighting the support or contribution of AI systems to important skills rather than their effect. The frameworks that we used for coding the articles might be considered as a second limitation. There is no consensus about 21st-century skills among researchers. However, we applied several frameworks from research to code the articles according to the most common 21st-century skills. In other words, the main skills and their subskills are limited to the frameworks that we addressed. Furthermore, as mentioned in the Theoretical framework section, these six skills are not specific to the 21st century alone: technological and economic advancement in the next century might require key skills such as collaboration and problem-solving. The third limitation is database selection. Although the WoS database contains high-ranking journals, other databases were not utilised to search for articles. Despite these limitations, the synthesis of this systematic review is crucial to provide an overview of skill development with the support of AI-based technologies in the higher education context.

Results

Twenty-first-century skills associated with AI-based tools

RQ1: What is the distribution of 21st-century skills supported by AI-based tools?
Our analysis of 37 empirical articles indicated that all main 21st-century skills are supported by AI-based tools (see Table 4). In other words, the usage of various AI-based tools might have the potential to foster communication, collaboration, creativity, ICT, critical thinking and problem-solving skills.

Essel et al. (2022) reported that AI and its subfields enable technologies to interact with end users in human-like conversations by answering users' questions. Our study revealed that these novel affordances might also be considered opportunities to strengthen higher education students' 21st-century skills. For instance, in Bailey et al.'s study (2021), students engaged with chatbots to improve their speaking skills in the English language, which was a useful and effective experience for enhancing students' communication skills. Additionally, Ouyang et al. (2023) conducted a study in a collaborative learning context. Team members within a collaborative group monitored their progress with the help of some visualisations in AI-powered dashboards. Such visualisations are created as an outcome of machine learning algorithms that use multimodal data from learners. AI-powered dashboards supported students in managing their

collaborative tasks. We also reviewed articles (e.g., Lin et al., 2021) addressing AI-based systems and creative thinking skills. Students planned, designed and created AI algorithms after engaging with AI-based augmented reality applications (e.g., Lin et al., 2021). According to our review, students' experiences with AI-based tools may lead to an increase in their ICT skills. For instance, Almufarreh et al. (2021) found that students benefitted from dashboards powered by machine learning during online distance education. The dashboards enabled students to better access course knowledge and materials and thus facilitated the creation of media content (Almufarreh et al., 2021).

Table 4
Twenty-first-century skills supported by AI-based tools

Skills	Subskills	*f*	Sample research
Communication skills (*f* = 19)	Competency in additional languages	11	Bailey et al. (2021)
	Competency in mother tongue	8	Huang & Liu (2021)
Collaboration skills (*f* = 14)	Interact effectively with others	5	Ouyang et al. (2023)
	Work effectively in diverse teams	3	Zheng et al. (2021)
	Manage projects	3	Ouyang et al. (2023)
	Guide and lead others	3	Liu et al. (2023)
Creativity skills (*f* = 11)	Think creatively	4	Avsec et al. (2022)
	Work creatively with others	4	S. Wang et al. (2023)
	Implement innovations	3	Y. Xie et al. (2023)
ICT skills (*f* = 14)	Access and evaluate ICT	3	Almufarreh et al. (2021)
	Use and manage information	4	Shobana et al. (2022)
	Create media products	4	Jokhan et al. (2022)
	Apply technology effectively	3	Essel et al. (2022)
Critical thinking skills (*f* = 16)	Clarification and/or linking ideas	9	Heugh et al. (2022)
	Assessment and/or justification	8	Pérez-Mercado et al. (2023)
Problem-solving skills (*f* = 23)	Information retrieval and integration	6	M. Wang et al. (2022)
	Goal elaboration and balancing	6	Lin et al. (2021)
	Action planning and decision-making	6	Y. Xie et al. (2023)
	Self-management	5	Nguyen et al. (2023)

We found that students' critical thinking skills can be supported by the opportunities provided by AI-based tools. Intelligent tutoring systems, for example, were deployed to provide students with personalised support when they worked on writing assignments and architecture design tasks (Avsec et al., 2021). More specifically, through recommendation and automated feedback, intelligent tutoring systems enabled students to clarify and link multiple ideas by leading them to be more critical of their writing and design tasks. According to the results from our review, problem-solving (f = 23) appeared to be the most common 21st-century skill related to AI-based tools. AI-based tools were exploited for four distinct purposes in the problem-solving process. In Pérez-Mercado et al.'s (2023) study, students interacted with a conversational agent named ChatbotSQL by asking some questions to solve a problem related to structured query language. ChatbotSQL supported students by reminding them of some prior knowledge and helping them make further decisions to solve the problem regarding database queries.

Types of AI-based tools supporting 21st-century skills

RQ2: What is the distribution of AI-based tools over the studies conducted to support 21st-century skills?
Our review revealed that the most widely harnessed AI-based technology is intelligent tutoring systems (e.g., adaptive learning systems and personalised learning platforms) (47%) (see Figure 1). According to Ouyang et al. (2022), intelligent tutoring systems offer an ideal platform for online distance education and hybrid education. It is important to note that distance or hybrid education is frequently applied in higher education contexts (Zhang et al., 2022). Thus, in some studies that we reviewed (e.g., Ouyang et al., 2023;

Y. Xie et al., 2023), higher education students engaged with intelligent tutoring systems during online education. Intelligent tutoring systems could be better integrated into various learning approaches (e.g., computer-supported collaborative learning and self-regulated learning). Zhou and Liu (2022) found that students optimised their individual learning process through the regulation of emotion due to the facial recognition feature of an adaptive learning system. Furthermore, a personalised learning platform named CoAST was utilised to support students' collaborative writing process (Shardlow et al., 2022). CoAST was reported to assist students in remembering and comprehending information from a text. In addition, due to AI's automation, an intelligent tutoring system enables students to receive timely and personalised support without the intervention of a human teacher (Zhang et al., 2022). Our review indicated that university students' need for interaction when improving their 21st-century skills might be met through an intelligent tutoring system (e.g., M. Wang et al., 2022).

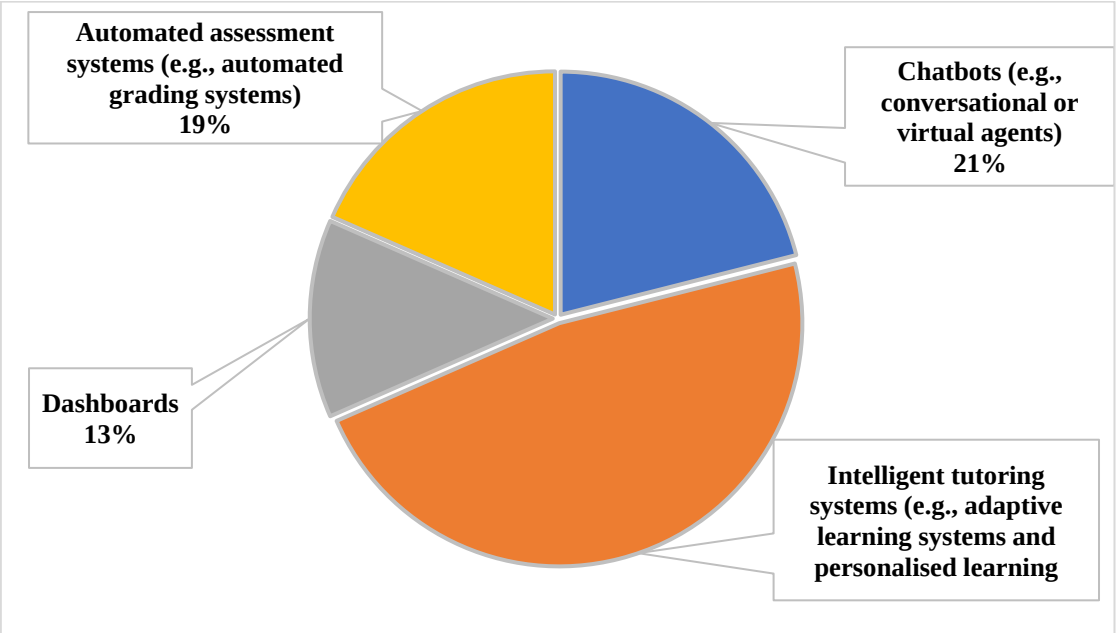

Figure 1. The distribution of AI-based technologies

AI-based dashboards were used mainly for monitoring and planning purposes associated with 21st-century skills (13%). We found that automated and customised recommendations from AI-powered dashboards provided students with flexible opportunities to regulate and monitor their individual and collaborative learning processes. For instance, machine learning-enabled dashboards predicted students' ICT literacy skills, giving students a chance to be aware of their skill development and providing instructions for early intervention (Jokhan et al., 2022).

Data modalities in research on AI and 21st-century skills

RQ3: What data modalities were gathered from participants in the empirical studies on AI-based tools and 21st-century skills?

According to our results, four main data modalities were gathered from the participants: self-reported (questionnaires, surveys) (22%), text (or discourse) (22%), user queries (input) (20%, and performance test (22%). Self-reported questionnaires or surveys were administered to measure participants' perceptions, attitudes, and self-efficacy in relation to 21st-century skills (see Figure 2).

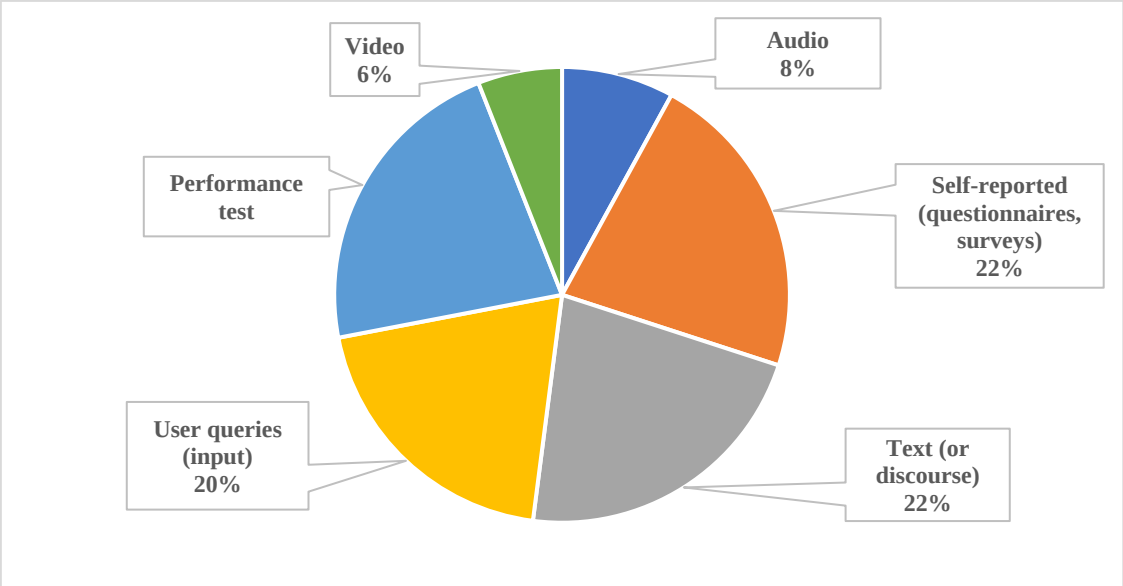

Figure 2. The distribution of data modalities

This data modality also helped researchers to collect participants' demographic information. S. Wang et al. (2023), for example, measured students' self-efficacy and creativity using predeveloped surveys. Text (or discourse) data were also collected to understand students' 21st-century skills. According to our review, text data were obtained from interviews with participants or from participants' interactions with AI-based tools (e.g., chatbot conversations or discussion boards in adaptive learning systems). Liu et al. (2023) asked semi-structured interview questions to reveal the benefits and challenges of an automated scoring system. Conversation text was also used to explore student–chatbot interaction regarding ICT skills (Essel et al., 2022). Performance tests were generally utilised at the end of an experimental process connected to 21st-century skills. For instance, in a quasi-experimental study, Taskiran and Goksel (2022) used a performance test to determine student achievement in a writing task. User queries or input provide trace data (e.g., log data) stemming from interactions between users and AI-based technology. Using an analytical approach, researchers obtained this kind of data from AI systems to reveal 21st-century skill development. For instance, H. Xie (2022) collected behavioural data from students (e.g., downloads and shares) to offer personalised recommendations for English reading texts through an intelligent tutoring system.

The functional affordances of AI-based tools for supporting 21st-century skills

RQ4: What are the functional affordances of AI-based tools for supporting 21st-century skills?

Our review revealed that AI-based tools have seven functional affordances for supporting 21st-century skills (see Table 5). Among these advantages, adaptive feedback was found to be the most prevalent (f = 20). This affordance refers to receiving responses from AI-based tools that are specific to the user. In order to create these user-specific responses, AI algorithms process users' data. For example, an analysis of multimodal discourse data yielded adaptive responses matching students' needs to improve their communication skills in a foreign language (Niu et al., 2022). According to our review, students have the opportunity to improve their 21st-century skills by engaging with AI-based tools (f = 20). Here, we define engagement as students' actual utilisation of AI-based tools. As reported in Almufarreh et al.'s (2021) study, students' development of ICT skills can be supported by using AI-based dashboards.

Table 5
Functional affordances of AI-based tools for 21st-century skills

Affordances	*f*	Sample research
Providing adaptive feedback for skill development	20	Shobana & Kumar (2022)
Engaging with students	15	Lin et al. (2021)
Automatically assessing constructs related to skills	11	Chu (2022)
Recommending learning materials and strategies	7	Huang & Liu (2021)
Predicting variables related to skills	5	Taskiran & Goksel (2022)
Profiling learners for further intervention	4	Zheng et al. (2021)
Monitoring individual and/or group progress	4	Almufarreh et al. (2021)

Another key functional affordance of AI technologies was the automated assessment of variables associated with 21st-century skills (*f* = 11). Automated assessment involves recognising and capturing students' data and automatically evaluating their responses related to 21st-century skills. For this automation process, natural language processing and automated speech recognition are embedded in AI-based technologies (Ahn & Lee, 2016). For instance, in foreign language or mother tongue learning, an automated scoring process facilitated the assessment of students' written or spoken conversations (e.g., Taskiran & Goksel, 2022). Similarly, some researchers benefitted from this opportunity to automatically evaluate problem-solving (Y. Xie et al., 2023) and creative thinking skills (Sung et al., 2022). Our review results also show that AI-based technologies might be beneficial for providing recommendations in terms of the development of numerous 21st-century skills (*f* = 7). For instance, in a collaborative learning setting, students can receive recommendations on regulation skills, supporting strategies and learning resources (Zheng et al., 2021). In the present review, predicting variables related to 21st-century skills (*f* = 5) and profiling learners for further intervention (*f* = 4) emerged as other functional affordances of AI-based tools. These affordances are commonly applied before interventions occur (e.g.,Taskiran & Goksel, 2022).

The challenges of AI-based tools in supporting 21st-century skills

RQ5: What are the challenges of AI-based tools in supporting 21st-century skills?
Although AI-based tools have many affordances for 21st-century skills, we observed some challenges caused by AI (see Table 6). Compared to the functional affordances of AI-based tools, our review revealed that the drawbacks of AI-based tools were scarcely reported. It is crucial to note that in the majority of the reviewed articles, the AI technologies deployed were presented as new technologies (being used for the first time) (Shobana & Kumar, 2022). Given the novelty of AI systems in terms of skill development, it is likely that researchers focused on the affordances of these technologies. As the novelty of AI diminishes, there is likely to be more empirical research on the challenges of AI systems.

Table 6
Challenges of AI-based tools for 21st-century skills

Challenges	*f*	Sample research
Accuracy of assessment	7	Sung et al. (2022)
Provision of personalised learning content	4	Essel et al. (2022)
Autonomy of decision	2	Ouyang et al. (2023)
Number of data modalities	2	Zhou & Liu (2022)

A few challenges related to AI-based tools for 21st-century skill development were reported in the reviewed studies, including accuracy of assessment, provision of personalised learning content, autonomy of decision and number of data modalities. Although automated grading applications facilitate exam scoring and decision-making on student performance, there are still concerns about the accuracy of the assessment process, which was found to be a considerable challenge in this review. Researchers also reported that it is sometimes challenging to provide students with personalised learning content. In order to train AI algorithms, multimodal data are needed from end users (Liu et al., 2023). It is then possible to create more personalised feedback using AI algorithms. However, without sufficient user-specific data, the feedback from AI systems might become more general. Our review results showed that this could

make it difficult for AI-based tools to improve users' 21st-century skills. The autonomy of decisions emerged as another challenge in the use of AI technologies. Whether final decisions should be made by AI or humans is a controversial issue. For instance, when automated systems evaluate students' communication skills in a foreign language, it is not easy to decide whether evaluation scores should be checked by human teachers (e.g., Ouyang et al., 2023).

The distribution of learning and teaching domains

RQ6: What is the distribution of learning and teaching domains in which AI-based tools were integrated to support 21st-century skills?

As illustrated in Figure 3, most of the articles (*f* = 13) were conducted on language learning, including mother tongue and foreign language skills. We observed that researchers utilised mainly chatbots and intelligent tutoring systems to support students' communication skills in either their mother tongue or an additional language (Huang & Liu, 2021). Computer science and engineering appeared to be fields where AI-based technologies were commonly utilised. This might have been because students and instructors in such fields are familiar with emerging technologies and can easily adopt AI systems to foster their skills (Zawacki-Richter et al., 2019).

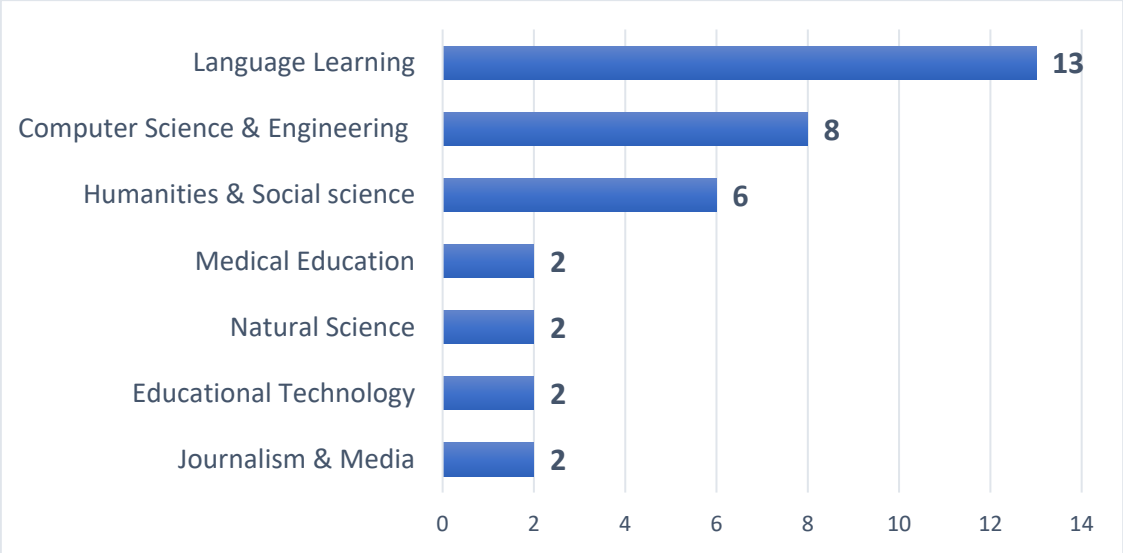

Figure 3. The distribution of learning and teaching domains

The distribution of AI technologies by learning and teaching domain is shown in Table 7. Intelligent tutoring systems were utilised mainly in the language learning and computer science fields. Chatbots were also observed as a predominant AI tool for language learning. Students in computer science benefitted from the engagement, automated assessment and adaptive feedback afforded by intelligent tutoring systems. For language learning, key affordances were prediction, recommendation and adaptive feedback from chatbots.

The use of AI technologies is also becoming more popular in the humanities and social science fields (S. Wang et al., 2023), which is reflected in our results (f = 6). The integration of AI-based technologies to support 21st-century skills is inevitable, since all stakeholders in higher education will be surrounded by AI and its subfields (Essel et al., 2022). We highlight that a variety of distinct fields in higher education (e.g., journalism and media, and medical education) have started to benefit from AI technologies. This could be an indicator of more AI integration in numerous fields in the near future.

Table 7
The distribution of AI-based tools by domains

Field	Chatbots	ITS	Dashboards	AGS
Language learning	4	5	2	2
Journalism & media	-	-	-	2
Computer science & engineering	2	4	-	2
Educational technology	-	1	1	-
Humanities & social sciences	3	-	1	2
Natural science	-	-	1	1
Medical education	1	-	-	1

Note. ITS: intelligent tutoring systems; AGS: automated grading systems

Discussion

Higher education is a crucial context in which students can be empowered with key and transferable skills such as problem-solving. AI-based educational technologies could be deployed to support students' skills. Therefore, it is important to conceptualise the functional affordances of these technologies for optimising skill development. Little is known about how the affordances of AI tools could foster students' key skills, namely collaboration, communication, critical thinking, creativity, problem-solving and ICT skills, which are regarded as 21st-century skills in this study. In order to fill this gap, we reviewed empirical studies on 21st-century skills and AI technologies. This is the first systematic review in higher education to provide an overview of the functional affordances of AI associated with 21st-century skills. We argue that these six skills are critical and necessary in the 21st century and will remain so in subsequent centuries, as suggested by other researchers (Dede, 2010; Fishman et al., 2016; Van Laar et al., 2020).

As a major finding, we found that the utilisation of certain AI-based tools might contribute to the development of multiple 21st-century skills (e.g., collaboration and critical thinking). Y. Xie et al. (2023) developed an AI-based system to increase student interaction in online learning, and their system supported both the problem-solving and creativity skills of students. Van Laar et al. (2017) suggested that 21st-century skills are closely associated with each other and that the integration of emerging technologies might contribute to various 21st-century skills. Consistent with this, we coded 18 articles in which AI-based tools supported higher education students' 21st-century skills. Furthermore, we found that students can improve manifold subskills of key 21st-century skills due to the functional affordances of AI systems (e.g., accessing information and creating media products). Based on the affordance theory (Gibson, 1977), the functional affordances of AI technologies could be regarded as the mechanisms through which such technologies support students' key skills. These mechanisms, for example, include adaptive feedback, prediction and recommendations. We highlight this conceptualisation as one of the main contributions of this study to research on the design, development, and implementation of AI in higher education. However, we also emphasise that revealing the actual effects of more sophisticated generative AI technologies such as ChatGPT requires an experimental study.

In the reviewed articles, intelligent tutoring systems were the most frequently used AI technology (47%), followed by chatbots (21%) and then automated grading systems (19%). We found that chatbots are commonly used to strengthen students' mother tongue and foreign language learning (and therefore their communication skills). Learning a foreign language requires constant practice in authentic contexts (Huang & Liu, 2021;). Our results suggest that chatbots might serve as a language partner, thereby contributing to students' communication skills. Furthermore, automated grading systems are useful in evaluating higher education students' 21st-century skill development. For instance, Kotlyar et al. (2023) empirically reported that automated scoring applications can support instructors in evaluating students' teamwork skills.

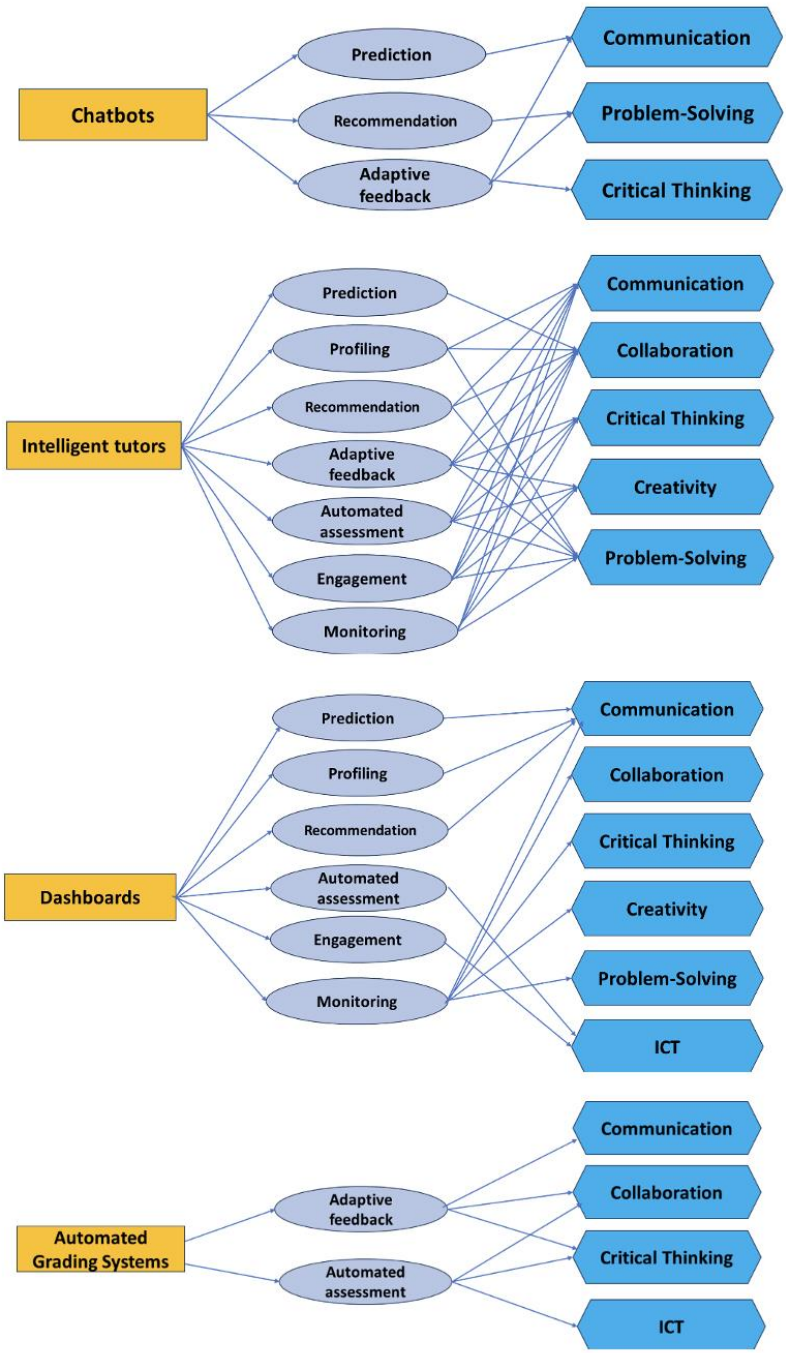

Figure 4. Functional affordances associated with 21st-century skills for each AI-based tool

It would be risky to give AI tools full autonomy to make decisions without prior expert evaluation (Berendt et al., 2020). Our review underlines this issue in terms of supporting skills. However, more creative questions from end users might lead to more creative responses from chatbots (Chang et al., 2022). In this regard, when students explore challenging questions by interacting with AI, they are more likely to think creatively (Pérez-Mercado et al., 2023). This interaction might enhance students' creative thinking (Heugh et al., 2022). In our review, we also found that audio (8%) and video (6%) data were gathered less than other data modalities. Järvelä et al. (2021) showed that multimodal data from various channels (e.g., audio and video) are valuable for capturing key moments and creating more objective visualisations in instructional processes. Therefore, we highlight a significant gap in terms of multimodal data collection for fostering 21st-century skills with the help of AI-based technologies.

According to our review, AI systems might support students in monitoring their individual or group progress associated with 21st-century skills (e.g., Zheng et al., 2021). Timely visualisations representing students' progress in terms of knowledge or skills were created with the help of machine learning algorithms. It is important to note that the affordances of prediction, profiling and monitoring stem from machine learning algorithms, which analyse users' data or data from their environment through their interaction with AI-based tools. For instance, during Japanese language learning, test questions were classified based on students' readiness. After taking the test, students were made aware of their strengths and weaknesses in terms of different topics (Chu et al., 2022).

Conclusion

We have provided an overview of the functional affordances associated with 21st-century skills for each AI-based tool. Figure 4 illustrates our overview of the reviewed empirical research in the higher education context. It is clear from our review that AI-based technologies have several functional affordances for supporting higher education students' 21st-century skills. Among these advantages, adaptive feedback plays a significant role as a facilitator in students' development of 21st-century skills. Some AI affordances are quite specific to certain AI technologies. For example, while monitoring is more prevalent within dashboards, adaptive feedback is a key functional affordance of chatbots.

In line with Figure 4, we can conclude that the utilisation of diverse functional AI affordances might support various skills. Intelligent tutors use a wide range of functional affordances of AI (e.g., prediction and profiling), thereby contributing to five 21st-century skills. Similarly, dashboard systems may support six skills through numerous AI affordances. The developers of chatbots and automated grading systems should focus on including more AI functional affordances, which would increase these technologies' ability to promote a wider spectrum of 21st-century skills.

The results of our review show that four distinct AI-based tools develop students' communication skills, mainly through adaptive feedback and recommendation (Figure 4). Problem-solving appears to be the most supported 21st-century skill benefitting from AI-based functionalities. More research is needed to demonstrate the functional affordances of AI technologies for promoting students' creativity and ICT skills.

Another gap that emerged from our review is that multimodal data are generally not being gathered from participants. As AI algorithms use reasoning to make decisions based on data, it is necessary to use multiple data channels to ensure more accurate outcomes. Such outcomes (e.g., prediction, assessment and feedback) could then be more effective and adaptive in supporting 21st-century skills. Indeed, the accuracy of outcomes is reported as one of the major challenges in integrating AI-based technologies into skill development. This is probably due to the low number of data modalities used to train AI algorithms. We also suggest that more empirical research dealing with supporting skill development through AI-based tools is needed in the fields of social science and humanities.

Author contributions

Author 1: Conceptualisation, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review and editing; **Author 2**: Data curation, Investigation, Formal analysis, Writing – review and editing; **Author 3:** Review and editing; **Author 4:** Review and editing.

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