Chou et al. *Research and Practice in Technology Enhanced Learning* (2025) 20:32
https://doi.org/10.58459/rptel.2025.20032

Research and Practice in
Technology Enhanced Learning

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Defining AI companions: a research agenda—from artificial companions for learning to general artificial companions for Global Harwell

Chih-Yueh Chou [1], Tak-Wai Chan [2] *, Zhi-Hong Chen [3], Chang-Yen Liao [4], Ju-Ling Shih [2], Ying-Tien Wu [2], Ben Chang [5], Charles Y. C. Yeh [2], Hui-Chun Hung [2] and Hercy Cheng [6]

*Correspondence:
chan@cl.ncu.edu.tw
Graduate Institute of Network Learning Technology,
National Central University,
No. 300, Jhongda Rd., Jhongli District,
Taoyuan City 32001, Taiwan
Full list of author information is available at the end of the article

Abstract

This paper examines and outlines the future exploration of AI companions, focusing on three main areas. Firstly, it defines AI companions as sophisticated AI entities designed for supporting and enhancing human experiences in daily activities, such as learning, working, and others. They encompass emotional, social, and practical aspects of daily life while fostering interactions and relationships with humans. Secondly, the paper provides a historical review of AI companions for learning (i.e., AI learning companions), offering an overview of their conceptualization, development, and utilization in educational contexts and insights into their potential future trajectory. Lastly, a research agenda is presented, which includes AI learning companions—outlining key questions, challenges, and goals for integrating AI companions into learning environments—and the pursuit of Global 'Harwell' (a portmanteau of 'harmony' and 'wellbeing'). This suggests that, in addition to transforming education, AI companions can contribute to individual wellbeing as well as broader humanitarian objectives. Beyond contributing to economic growth and efficiency, it is fundamentally important to address the most pressing global challenges or human crises of our time, foster understanding and cooperation among researchers and practitioners in different fields, and hence pave the way toward a future world marked by Global Harwell. To further advocate and demonstrate the pivotal role of AI companions in achieving these genuine objectives, we propose the General Artificial Companion Hypothesis. All these endeavors, however, begin with AI companions for learning. As Mandela said, "Education is the most powerful weapon which you can use to change the world."

Keywords: AI companions, AI learning companions, Artificial companions, Artificial general intelligence, General artificial companions, Artificial intelligence in education, Intelligent computer assisted learning

From who we are to who they will be,
from where we are to where they will be,
education steers the path.

Introduction

Arguably, the most significant implication for education arising from the launch of ChatGPT in 2022 is its role as an artificial companion (or AI companion; we shall use these terms interchangeably) for learning, specifically as an AI learning companion. Clearly and rapidly, the significance of AI companions extends to other domains, including health, entertainment, work, sports, and almost all facets of our lives.

With the advent of generative AI technologies, such as ChatGPT, the public can now envision the Turing Test being passed—a scenario where a human interrogator cannot distinguish between a human and a machine in a text-only conversation. Rapid advancements in AI, the internet, the metaverse, and technologies like augmented reality, advanced robotics, the Internet of Things, quantum computing, and blockchain are poised to expedite the development of AI companions, both virtual or robotic. These companions are expected to demonstrate human-like intellectual, emotional, social, and even value-based behaviors. In various subtle ways, the power of such digital resemblance may make it challenging for us to discern whether the AI companion we are interacting with is a real person or an artificial entity. Recently, AI companions have garnered significant interest and have demonstrated considerable promise. With the advancement of AI, an AI companion could be a patient and caring 'superhuman' available around the clock, potentially approaching or even surpassing human experts in various domains. For example, Deep Blue defeated a chess master in 1997 and AlphaGo achieved victories against multiple human Go masters starting in 2015. ChatGPT has the capabilities to check syntax, rewrite sentences, translate into different languages, generate content and answer various questions. However, it sometimes provides inaccurate information or even fabricated 'hallucinations,' leaving room for improvement (Alkaissi & McFarlane, 2023; Rasmussen et al., 2023; Tlili et al., 2023). Nevertheless, in a panel during a workshop in 2022 [1], Tak-Wai Chan, one of the originators of AI companions for learning, said: 'The AI learning companion is almost there!' In the future, we will find numerous AI companions around us.

The rest of the paper is organized as follows. The next section discusses AI companions and AI learning companions, covering AI in roles as tools, assistants, or companions; and definitions of AI companion and AI companionship. Following that, the third section presents the origin of AI learning companions. The fourth section proposes a research agenda for AI learning companions by outlining four research questions. In the fifth section, the pedagogical designs of AI learning companions in specific subject matters are explored.

The sixth section addresses the challenging research issue of pursuing Global Harwell with the support of AI companions, aiming to tackle noted global crises while alleviating concerns about potential negative impacts of AI on humanity. The final section provides a conclusion.

AI companions and AI learning companions

AI tools, AI assistants, and AI companions

In adopting AI across various domains, such as education, healthcare, entertainment, finance, retail, and transportation, we observe the spectrum from viewing AI merely as a tool to considering AI as an assistant and even as a companion (see Figure 1). The spectrum covers a wider range, and the three roles often become blurred. Nevertheless, we can roughly differentiate them by their complexity or depth of interaction with us. As a tool, AI acts as a piece of equipment that we manually operate to accomplish a task. As an assistant, AI aids us by performing certain tasks or providing intricate support to complete a task. Clearly, generative AI can now or soon serve as an AI assistant in many domains, such as developing programming code, creating animations, and providing legal advice.

The epoch of AI companions is approaching. As a companion, the interactions between AI and the human user involve mixed initiative: sometimes the human initiates a dialogue or an activity to which the AI responds, and vice versa. Beyond the specific purpose of fulfilling the current task, offering sophisticated responses requires consideration of the human user's intellectual, emotional, social, and value dimensions. This requires the companion to acquire a 'memory' of the user's past experiences and beliefs; in other words, it necessitates a user model. We should also be cognizant that a companion's response, when incorporated with such nuanced and thoughtful consideration, will subtly yet significantly influence the human user's perspectives across various dimensions.

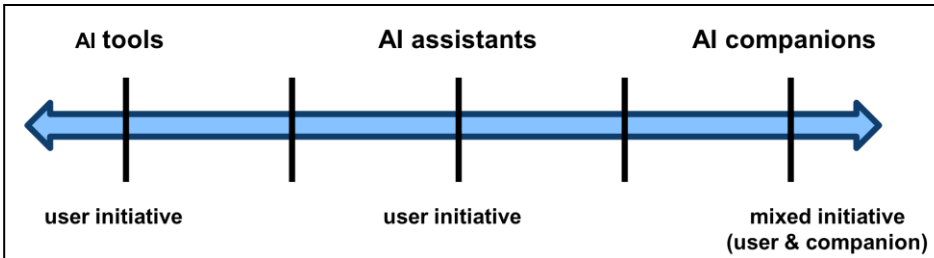

Fig. 1 Spectrum of human-AI relationships

AI companions and human-AI companionship

What is a companion, and what defines companionship? First of all, companionship is a type of positive dyadic social relationship, which involves the following six features: emotional support, joint activities, dependability and faith, mutual respect, dialogue and exchange, and enjoying togetherness. Emotional support refers to offering empathy, understanding, and comfort. Joint activities mean engaging in common interests or activities together. Dependability and faith imply being dependable and trustworthy. Mutual respect indicates valuing each other's opinions, feelings, and needs. Dialogue and exchange involve open and honest discussion about thoughts and feelings. Enjoying togetherness suggests finding pleasure in spending time together.

Now, can we consider our mother, spouse, child, friend, teacher, tutor, fellow classmate, or even our pet as companions? If so, assuming a human or creature is our companion, our companionship can be defined by our 'relationship,' such as a parent-child or doctor-patient relationship, and 'interactions,' which include both past and prospective interactions.

We may consider the parent-child relationship as an example to further explore the concept of 'relationship.' This relationship involves two actors, each assuming a specific 'role': one as the parent and the other as the child. The parent is responsible for everything related to the child's growth, while the child learns from the parent and follows their instructions. Thus, we can see that the roles within a relationship define the overarching goal of their interactions. By 'overarching goal,' we mean a goal composed of many, or even numerous, sub-goals to achieve a shared, comprehensive, yet specific objective. 'Interactions' here are viewed as a series of action-and-reaction pairs between the two actors, continuing throughout their relationship, from past to present and into the future, all intended to fulfill their overarching goal.

Perhaps we can define:

companionship of two actors = (relationship, overarching goal, interactions)

Involving just two actors, a human and an AI companion, this formulation represents the simplest and most basic form of companionship. Naturally, this definition can be extended to encompass companionship among a group of actors. Indeed, in our everyday lives, we engage in both dyadic and group companionships. In the future, we will have many AI companions around us, some of them representing delegates of our human friends, relatives, or people we may or may not be acquainted with (as in the Metaverse environment).

In this paper, most of our examples focus on dyadic companionship, where one actor is an AI learning companion and the other is a human learner. The overarching goal is educational.

Nevertheless, with a bit of imagination, some challenging questions may arise from the definition of companionship. Suppose the group of actors includes all humans and all existing AI companions. Given the extremely complex relationships and interactions among all the actors, what would be the overarching goal of this global companionship? If we focus solely on education, then what would be the overall educational goal for global learning companionship? We shall come back to these questions in a later section of this paper.

The origin of artificial learning companions and subsequent works

Inspired by the potential applications of machine learning in education, Chan and Baskin (1988) proposed the concept of learning companions. This concept envisions the computer acting as a student's learning companion, akin to the Chinese proverb 'Studying with the Prince,' to enhance learning through such companionship (see Figure 2).

Theoretical explanations for the benefits of learning alongside companions

(1) Zone of proximal development

Chan and Baskin (1988) cited Vygotsky's *zone of proximal development* as the theoretical basis for artificial learning companions (ALCs). This concept explains the potential benefits to student learning by describing the gap between a student's independent problem-solving ability and their potential ability with adult guidance or collaboration with peers (see Figure 3). They also highlighted how this concept helps explain why princes in ancient Chinese empires learned more effectively when studying with their companions (Chan & Baskin, 1988).

Fig. 2 Learning with the Prince (Chan & Baskin, 1988)

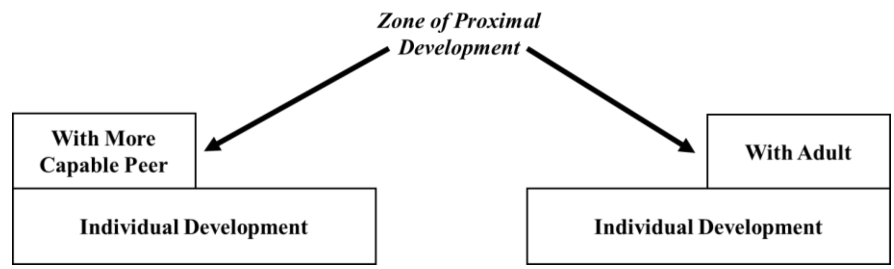

Fig. 3 Vygotsky's hypothesis on the zone of proximal development

(2) Cognitive conflicts and resolution

Chan and Baskin (1990) also referred to Doise and colleagues' work (1975)—the emergence of social-cognitive conflicts and active conflict resolution—to explain improved cognitive development through interaction with peers. In a dyadic setting, both face alternative and conflicting solutions that, while not always yielding the correct response, may introduce relevant dimensions for the progressive formation of new cognitive processes (Mugny et al., 1981). Unlike a teacher's guidance, which aims to steer the student toward what is perceived as the correct path, cognitive conflict presents a dilemma of conflicting perspectives that both students must resolve.

Cognitive conflict frequently arises because rarely do two students' knowledge overlap completely. When cognitive conflict occurs, students are prompted to re-evaluate their thinking, seeking out alternative perspectives suggested by the conflict, while also remaining vigilant for potential relevance (Chan & Baskin, 1990). In essence, both students must diagnose and evaluate the issues brought to light by cognitive conflict, while also defending their own perspectives (Figure 4).

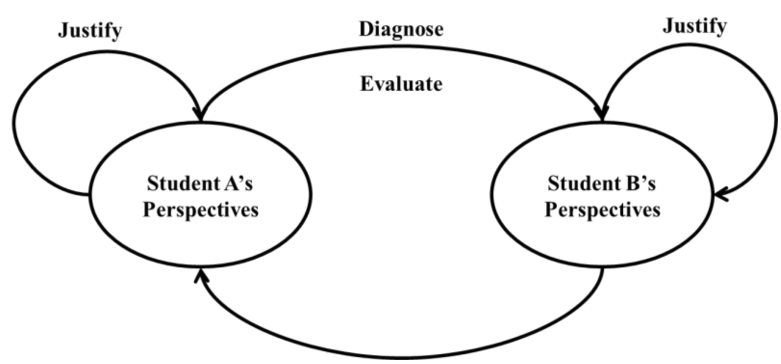

Fig. 4 Cognitive conflict and resolution between a dyad (Chan & Baskin, 1990)

(3) Dynamic cognitive changes

As an abstraction of understanding the "knowledge dynamics" in learning environments of different social context (Chan, 1991), we may view a person's current knowledge in a domain as their personal interpretation, evolving through learning and influenced by their background, culture, and learning environment. This evolving interpretation, termed interpreted knowledge, varies over time and represents their understanding at any given moment, encompassing both correct and incorrect concepts. Versions of interpreted knowledge are considered higher when they articulate more knowledge, fewer misconceptions, and more adaptable representations.

In traditional teacher-guided learning, the teacher aims to align the student's evolving interpreted knowledge with their own static, advanced understanding. The teacher monitors learning activities and provides support to facilitate knowledge convergence, with the student's evolving versions of interpreted knowledge *converging* towards the teacher's authoritative knowledge (Figure 5).

Conversely, when learning with a peer, students engage in the interaction process of cognitive conflict and resolution, leading to revising their own versions of interpreted knowledge and merging (Figure 6) into a shared understanding of the teacher's authoritative knowledge, contrasting with the hierarchical student-teacher dynamic which can limit such exchanges due to differing social status and knowledge levels. Learning with peers promotes the synthesis of evolving interpretations, fostering a dynamic learning experience that contrasts with the hierarchical alignment in teacher-led environments.

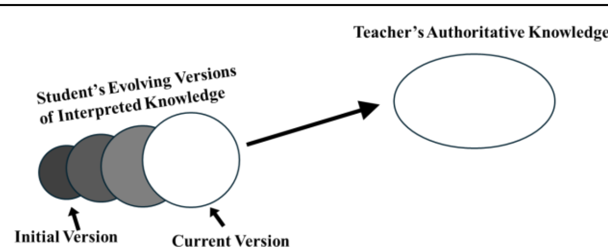

Fig. 5 Student's interpreted knowledge evolving towards teacher's knowledge (Chan, 1991)

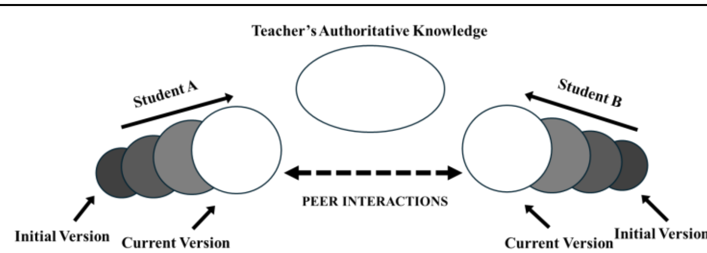

Fig. 6 Students' interpreted knowledge co-evolving towards teacher's knowledge (Chan, 1991)

Two possible design approaches

Chan and Baskin (1988) described two approaches to designing ALCs: *simulation and machine learning*. "In the simulation approach, the companion's performance is controlled by the system in order to adapt to the student. A simulated companion may have deliberate sub-optimal behavior in order to match skill with the student. On the other hand, in the machine learning approach, the growing knowledge of the companion, which results in improved performance, is acquired through machine learning techniques. In this approach, the student's learning is more likely to benefit from observing how the companion learns, as the companion explains their learning process, discoveries, and hypotheses derived from what they have learned [2] (p. 199)."

Chan (1991) developed the first ALC prototype system, called Integration-Kid, by adopting the simulation approach for learning indefinite integration in first-year undergraduate calculus. The system demonstrated several interaction scenarios between a human student and an ALC, with occasional interventions by an artificial teacher.

Chan and Baskin (1988) also highlighted that the paradigm of the ALCs spans a wide spectrum of design possibilities, influenced by the potential variations in the number and identities of both human students and ALCs. For example, "it is possible to have no teacher involved. For example, in learning simple linear equations, the student may provide rules (e.g., distributive rule) and some examples to the learning companion. Then the student may observe how the companion solves the problems and improves performance. In this way, the student *learns how to learn by teaching the learning companion*…To the other extreme, it is possible to have multiple (virtual) teachers with different persona. For example, there may be a patient teacher and a demanding teacher. The student may choose one of them to adaptively respond to their own learning style…which means more than one ALC with different knowledge level or personas involved in the learning environment (p.199)."

Subsequent works

Subsequently, more ALCs were designed and implemented with diverse roles supporting various learning activities. For example, Distributed WEST facilitates collaborative and/or competitive learning among students using two connected computers with other students or ALCs (Chan et al., 1992). Reciprocal Tutoring Systems enable students to participate in reciprocal tutoring activities where ALCs act as peer tutors, tutees or competitors (Chan & Chou, 1997; Chou et al., 2002). EduAgents provide students heterogeneous ALCs, including two strong ALCs and two weak ALCs (Hietala & Niemirepo, 1998).

Chou et al. (2003) defined ALCs as "computer-simulated characters with human-like characteristics that plays a non-authoritative role in a social learning environment." These human-like characteristics encompass competence, emotions, beliefs, behaviors, appearance, personality, and more, which can be expressed or displayed in text, images, animations, multimedia, virtual reality, augmented reality, natural language processing, speech recognition and synthesis, and image recognition or through robots. They categorized ALCs by roles, such as competitors, collaborators, tutees, peer tutors, troublemakers, critics, or clones, engaging students in various social learning activities like collaborative learning, reciprocal tutoring, and learning by teaching. It is noteworthy that this paper broadens the definition to include not only non-authoritative roles but also authoritative roles like parents, tutors, and experts who possess greater knowledge and social status.

Numerous studies have demonstrated that ALCs enhance students' learning performance (e.g., Atkinson, 2002; Castro-Alonso et al., 2021; Graesser et al., 2005; Kim et al., 2007; Kulik & Fletcher, 2016; Lester et al., 1997; Li et al., 2022; Lusk & Atkinson, 2007; Ma et al., 2014; Moreno et al., 2001; VanLehn, 2011), motivation (e.g., Baylor, 2009; Kim et al., 2007; Lester et al., 1997; Liu et al., 2024; Moreno et al., 2001; Schroeder & Adesope, 2014), and self-regulation (e.g., Harley et al., 2018; Karaoğlan Yılmaz et al., 2018).

ALCs have been developed with various appearances or representations. Animated pedagogical agents provide human-computer interaction through face-to-face mixed-initiative dialogue (e.g., Blair et al., 2007; Clarebout et al., 2002; Davis, 2018; Gulz & Kakke, 2006; Johnson et al., 2000; Kim & Baylor, 2006; Kim et al., 2006; Lester & Stone, 1997; Ryokai et al., 2003; Sikström et al., 2022; Woo, 2009). Animal companions provide pet-like companionship to students (e.g., Chen, 2012; Chen et al., 2007, 2011). Learning companion robots feature a robotic appearance combined with human-like expressions, including voice, facial expressions, gestures, and motions (e.g., Cagiltay et al., 2022; Cheng et al., 2021; Ho et al., 2021; Hsieh et al., 2015; Hsu et al., 2007; Kory & Breazeal, 2014; Lfelebuegu, 2024; Liu et al., 2024; Lubold et al., 2021; Michaelis & Mutlu, 2018; Spitale et al., 2022; Wang et al., 2009; Wei et al., 2011; Zinina et al., 2023). Chatbot companions utilize natural language processing techniques to communicate with students in natural language (e.g., Huang et al., 2022; Huang et al., 2008; Hwang & Chang, 2023; Kim et al., 2022; Kuhail et al., 2023; Liu et al., 2024; Okonkwo & Ade-Ibijola, 2021; Ruan et al., 2019; Skjuve et al., 2021). More subsequent works are described in the next section along the discussion on the research agenda.

Research agenda of ALCs

Needless to say, the research agenda builds on both past and current research, with an eye looking toward the future. This study proposes a research agenda of ALCs, including four research issues and five components (Figure 7).

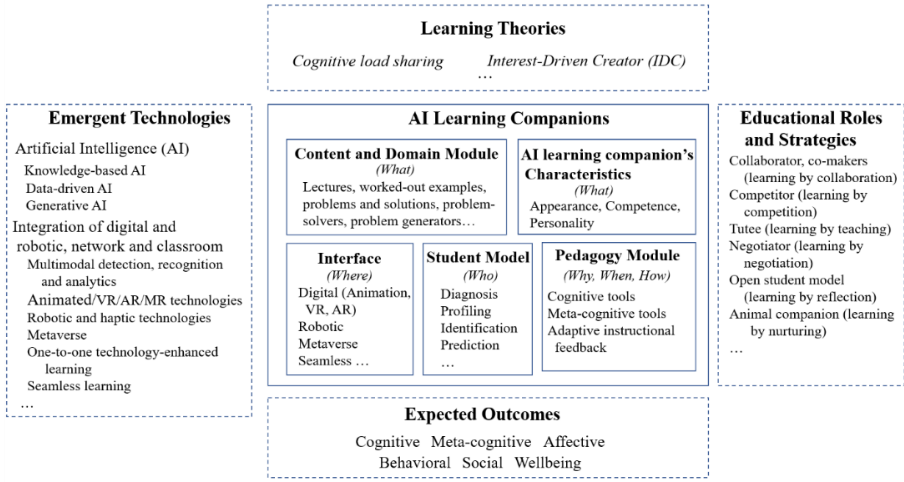

Fig. 7 Research agenda of ALCs

The four research issues include emergent technologies, learning theories, educational roles and strategies, and expected outcomes. The first research issue concerns the use of emergent technologies to support the design of ALCs. Technologies like knowledge-based, data-driven, and generative AI enable ALCs to adapt to students. In addition, animated, VR (virtual reality), AR (augmented reality), MR (mixed reality), robotic and haptic technologies, metaverse, and other seamless learning technologies (Chan et al., 2006; Looi et al., 2010) provide diverse forms and interaction modes of ALCs. The second research issue explores suitable learning theories for designing ALCs. For example, the cognitive load sharing approach offers six design dimensions to design ALCs with scaffolding and fading strategies to assist students in learning (Chou & Chan, 2016). Interest-driven creator theory (IDC Theory) provides a framework, including interest loop, creation loop, and habit loop, to design ALCs to foster students as interest-driven creators (Chan et al., 2018). The third research issue investigates the educational roles and strategies of ALCs. For example, ALCs can act as tutees, enabling students to learn by teaching ALCs (Chan & Chou, 1997; Chou et al., 2002; Uresti & Du Boulay, 2004), or as negotiators, facilitating learning by negotiation with ALCs (Chen et al., 2019; Chou et al., 2015, 2018). The fourth research issue examines the expected outcomes and evaluations of ALCs. ALCs can be designed to enhance students' cognition, meta-cognition, affection, behavior, social interaction, and wellbeing. Evaluations should assess the benefits and impacts of ALCs across these dimensions. These four research issues are further addressed at the next section.

The five components of ALCs that provide adaptive assistance to help students learn include content and domain module, ALC's characteristics, interface, student model, and pedagogy module (Chou et al., 2003). First, the content and domain module determines *what* students will learn. It generally contains lectures, worked-out examples, problems and solutions for students to study and practice. In addition, problem-solvers generate correct solutions of problems as models for students, while problem generators provide appropriate problems for practice and assessment. Second, the student model identifies *who* the learner is by diagnosing students' mastery levels and misconceptions, profiling students' characteristics, identifying specific learning behaviors, patterns, or tendencies, as well as predicting learning behaviors and performance (Abyaa et al., 2019; Bakhshinategh et al., 2018; Chrysafiadi & Virvou, 2013; Nakic et al., 2015; Romero & Ventura, 2010), which is crucial for adaptive assistance. Third, the pedagogy module guides *why*, *when* and *how* to support learning interactions with ALCs. Cognitive tools (e.g., concept map) and meta-cognitive tools (e.g., self-regulated learning tools) can be provided (*how*) as scaffolding (*why*) for students at the initial learning stage and fade out later (*when*). When the student model detects that a student has a misconception, the ALCs immediately (*when*) provides adaptive and instructional feedback (*how*) to help students to find out and correct their misconceptions (*why*). ALCs can provide various kinds of instructional feedback, such as mentoring, tutoring, prompting, questioning, guiding, etc. Fourth, ALCs can be designed with various characteristics (*what*), such as appearance (e.g., human or robot, young or old, attractive or less attractive) (Abubshait & Wiese, 2017; Baylor, 2009; Shiban et al. 2015), competence (e.g., strong, intermedia, or weak) (Chou et al., 2002; Hietala & Niemirepo, 1998), and personality (e.g., passion or calm) to fit diverse student preferences. Fifth, the interface defines the environmental location of *where* ALCs appear, whether digital (e.g., animated, VR, AR), robotic, within a metaverse, or seamlessly integrated across these platforms.

Research issue #1. How are emergent technologies used to support the design of ALCs?

Two emergent technologies have been applied to develop ALCs: AI in education and the integration of digital and robotic technologies in networked and classroom learning environments.

Artificial Intelligence in education

AI has emerged as a transformative force in education, revolutionizing traditional teaching methods and fostering personalized learning experiences. Historically, the trends and developments of AI in education can be divided into three periods: knowledge-based AI, data-driven AI, and generative AI.

Knowledge-based AI leverages rule-based systems, semantic networks, and constraint-based modeling to replicate human-like reasoning and decision-making. In an educational context, knowledge-based AI can be employed to design intelligent tutoring systems that mimic a teacher's expertise, such as Cognitive Tutor (Koedinger et al., 1997), AutoTutor (Graesser et al., 2005), and Betty's Brain (Biswas et al., 2016). These systems assess a student's knowledge, identify gaps, and provide targeted feedback or supplementary materials. For example, semantic networks can be used to map relationships between different concepts, helping students grasp complex subjects with interconnected ideas.

Data-driven AI relies on Bayesian networks (Baker et al., 2008), machine learning (Kochmar et al., 2022), and deep learning (Chiu et al., 2022) to derive meaningful insights by analyzing vast datasets of student learning or dialogues between students and teachers. For example, learning analytics, a subset of data-driven AI, encompasses the measurement, collection, analysis, and reporting of data related to learners and their contexts (Du et al., 2021). This process assists educators in making data-driven decisions to enhance teaching strategies and curriculum design. Additionally, learning analytics can be applied to help ALCs assess student performance, identify learning patterns, and dynamically adjust content delivery to meet individual needs.

Generative AI introduces a creative dimension to education (Chiu, 2023). Generative AI involves systems that can generate new content, such as text (Baidoo-Anu & Ansah, 2023), images (Vartiainen & Tedre, 2023), or even entire learning modules. This capability is particularly useful for creating personalized learning materials, interactive simulations, and virtual environments. For instance, generative AI can develop adaptive quizzes based on a student's progress, ensuring that the difficulty aligns with their current proficiency level. Moreover, large language models (LLMs) like GPT-4 enhance the ability of generative AI to understand and produce human-like text, which can be utilized in tutoring systems, essay feedback, and language translation tools (Bozkurt, 2023; Topsakal & Akinci, 2023). Additionally, retrieval-augmented generation (RAG) combines the strengths of LLMs and information retrieval systems to provide highly accurate and contextually relevant answers (Pan et al., 2024), enabling ALCs to offer students precise and comprehensive information throughout their learning process.

The integration of these AI approaches into education is providing ALCs to foster a more dynamic and tailored learning experience. Teachers can benefit from AI-driven tools that automate administrative tasks and from ALCs that assist with answering students' frequent questions or problems, allowing them to focus on providing deeper individualized instruction and mentorship. Students, in turn, experience personalized learning paths, immediate and adaptive feedback from ALCs, and engaging educational content. As technology continues to advance, the role of AI in education is expected to expand, offering even more sophisticated solutions to address the diverse needs of learners in the digital age.

Integration of digital and robotic technologies in networked and classroom learning environments

Emergent technologies are pivotal enablers in exploring ALCs. Digital and robotic technologies, along with the fusion of networked and classroom learning environments, presents numerous intriguing research issues and opportunities for ALCs (Rizk, 2020). Elaborations on some issues are shown as follows:

(1) Multimodal detection, recognition, and analytics

ALCs can communicate with students through multimodal interactions, such as text, speech, images, and actions. Therefore, ALCs receive multimodal data from students and their environments. These interactions and data require various detection, recognition and analytics techniques for student modeling, such as natural language process (Di Mitri et al., 2018), speech recognition and translation (Bezemer & Jewitt, 2010), eye-gaze tracking (Biswas & Langdon, 2015), gesture and action detection (Sharma & Giannakos, 2020; Vatral et al., 2023), and image and video analysis (Turk, 2014). Multimodal learning analytics provide a clearer picture of student's learning processes and statuses, and they bring more accurate predictions through the translation, coordination, alignment or fusion of multimodal data than a single data source (Baltrušaitis et al., 2019; Cukurova et al., 2020).

(2) Animated/VR/AR/MR technologies

Animated, Virtual, Augmented, and Mixed Reality technologies are transformative mediums for ALCs. Beyond the graphical user interface, these technologies provide spatial and experiential interfaces that can mimic real-world scenarios or create entirely new, controlled environments for learning (Baker, 2021). Research questions may focus on how the immersive nature of these technologies affects cognitive load, engagement, and the effectiveness of personalized feedback provided by ALCs.

(3) Robotic and haptic technologies

Robotic technologies bring ALCs into the physical world, allowing for more haptic or kinesthetic interaction with learners. For example, Matthieu and Dominique (2015) explored the interaction between artificial companions and children in everyday life, focusing on a coaching application where two artificial companions (a Nao robot and a virtual agent) teach children the basics of drums (Matthieu & Dominique, 2015). This is particularly crucial in fields like medicine, engineering, or craftsmanship, where tactile feedback is essential. In the context of adult education, robot-assisted language learning (RALL) can significantly enhance interaction and collaboration. For instance, a study by Engwall and Lopes (2022) demonstrated how robots could facilitate conversational practice in a second language, providing immediate feedback and encouraging more natural language use. Research in this area could explore the effectiveness of robot-assisted ALCs compared to traditional hands-on training methods. Furthermore, how can haptic technologies be integrated to simulate tactile feedback realistically?

(4) Metaverse

The Metaverse represents a frontier for the development of ALCs, offering a persistent, digital universe where learning can happen synchronously or asynchronously (Baker, 2021). Integrating ALCs into the Metaverse enables endless possibilities for collaborative learning, social interaction, and even cultural exchange. For instance, avatars can represent students and ALCs, providing an engaging and immersive experience tailored to individual learning styles and preferences. These avatars can interact in real-time, facilitating a more dynamic and interactive learning environment (Mozumder et al., 2022). Researchers might investigate how ALCs in a Metaverse setting affect student motivation, social learning, and global educational equity. Using avatars allows for personalizing learning experiences, creating a sense of presence and emotional connection that can enhance engagement and retention (Lee et al., 2021). Moreover, ALCs can provide instant feedback, adapt learning paths based on student progress, and offer support in various subjects through interactive simulations and virtual environments (Ayeni et al., 2024). This integration of ALCs in the Metaverse supports individual learning and promotes social and collaborative learning, breaking down geographical barriers and fostering a global learning community.

(5) One-to-one technology-enhanced learning

ALCs could be personalized one-to-one to cater to individual learners' unique learning styles and paces (Chan et al., 2006; Mirata et al., 2020). Chen et al. (2011) introduce the concept of animal companions in technology-enhanced learning. These virtual characters encourage students to engage in learning activities, a principle that can be applied in one-to-one learning environments (Chen et al., 2011). Advanced machine learning algorithms could analyze learner data in real-time to adapt instructional materials and strategies. Research here might focus on the ethical considerations of data collection and the efficacy of adaptive learning models.

(6) Seamless learning

Seamless learning (Chan et al., 2006) aims to continue learning experiences across various contexts—whether formal or informal, indoor or outdoor. ALCs, when designed with seamless learning in mind, must consider transitional support, context-aware resources, and continuous assessment for learners on the go. Research could focus on the technological challenges of context awareness and the pedagogical implications of learning continuity.

In summary, integrating various technologies in developing ALCs introduces multifaceted research dimensions. Each technological avenue—immersive realities, tangible robotics, expansive Metaverses, personalized one-to-one settings, or contextually seamless environments—offers research issues and pedagogical potentials that warrant rigorous scholarly investigation.

Research issue #2. Are there learning theories suitable for designing ALCs?

Currently, there exist learning design theories, such as self-regulated learning, experiential learning, cognitive apprenticeship, problem-based learning, and others. Nearly all of these theories can contribute to the design of ALCs. Two learning theories particularly pertinent to the design of ALCs are presented: Cognitive Load Sharing and Interest-Driven Creator Theory.

Cognitive Load Sharing

As discussed previously, Vygotsky (1978) proposed the concept of the *zone of proximal development*, which is the difference between tasks that children can perform independently and those that they can accomplish with assistance. The assistance acts as scaffolding provided by more knowledgeable peers or adults and includes strategies such as breaking down tasks to reduce complexity and difficulty, modeling tasks for children, and providing feedback to help them complete the tasks. Scaffolding can be provided by ALCs (Chan & Baskin, 1988). The advantages of using ALCs as a source of scaffolding include their ability to be designed for specific pedagogical purposes and adapted to individual students, thereby creating an effective learning environment. Chou and Chan (2016) proposed a Cognitive Load Sharing theoretical approach for designing ALCs, incorporating scaffolding and fading strategies to assist students in learning. This approach involves six dimensions, which create a design space for various ALC designs.

First, the task partition dimension concerns whether and how a learning task can be appropriately divided into sub-tasks so that they can be handled by different agents. Some tasks naturally consist of multiple sub-tasks. For example, comprehension involves four key activities: summarizing, questioning, clarifying, and predicting (Palinscar & Brown, 1984). In reciprocal tutoring, a learning task can be partitioned into 'tuteeing' and 'tutoring' for two agents. Second, the social scaffolding dimension addresses how sub-tasks are assigned to different agents. These agents can include human teachers, human peers, or ALCs. Generally, a reciprocal protocol is adopted, allowing students to alternate between handling different sub-tasks and gradually learning each one. Third, the scaffolding tools dimension considers the types of scaffolding tools that can be provided to help students complete sub-tasks. These tools include cognitive tools, meta-cognitive tools (e.g., self-regulated learning tools), and communication and collaboration tools. Fourth, the scaffolding and fading dimension concerns when and how social scaffolding and scaffolding tools are gradually removed (i.e., fading) and whether students can still complete learning tasks without them. Fifth, the student modeling dimension addresses how to apply student modeling techniques to create adaptive learning environments that optimize student learning. Sixth, the benefit-cost trade-offs dimension considers the trade-offs between the benefits of social scaffolding, scaffolding tools, scaffolding and fading, student modeling, and the costs associated with their implementation. In sum, the Cognitive Load Sharing approach provides a six-dimensional design space for developing various ALC designs with scaffolding and fading strategies.

Interest-Driven Creator Theory (IDC Theory)

IDC theory (Chan et al., 2018) describes how to nurture students as interest-driven creators through three anchored concepts: interest, creation, and habit. Each concept is represented by a loop that delineates its components in a circular process, namely, the interest loop, the creation loop, and the habit loop. IDC provides a framework for designing learning activities, where ALCs can be tailored for specific pedagogical purposes to nurture students as interest-driven creators according to their individual needs. In other words, IDC theory offers significant educational goals and insights for designing ALCs as effective scaffolding tools or learning environments.

First, the interest loop consists of three components: triggering interest, immersing interest, and extending interest. Triggering interest involves designing pre-activities that induce interest in the forthcoming learning activity, such as evoking students' curiosity and desire to know new knowledge. Immersing interest aims to design learning activities that fully engage students' attention, and achieve a 'flow' immersive mental state. Extending interest relates to designing post-activities to extend student interest in the domain after the immersive learning activity. Second, the creation loop consists of three components: imitating, combining, and staging. Imitating involves gaining knowledge to form background knowledge. Besides absorbing knowledge independently, students may observe examples and imitate others. Combining is the actual process of creation, generating new products through transformations and re-combinations of existing ideas or artifacts. Staging provides opportunities for students to present, describe, and demonstrate their creations to an audience, thereby receiving feedback on the quality of their creations and understanding factors such as novelty and values. Third, the habit loop consists of three components: cuing environment, routine, and harmony. Cuing environments are habit triggers, or signals to the brain, so a habit forms when a specific behavior is initiated consistently in the cuing environment. Routine refers to the habit loop in which the creation activities that students repeat regularly, similar to the daily routine governed by the school timetable. Harmony refers to the outcomes of habits, where students may realize their energy has been well invested and their needs are fulfilled. Harmony provides a sense of satisfaction and inner serenity, allowing students to feel at peace with their surroundings and the world.

Based on IDC theory, various ALCs could be designed to benefit student learning in affective, cognitive, and behavioral dimensions. First, for the affective dimension, ALCs design could evolve from a "motivation" facilitator to an "interest" facilitator. The former focuses on motivation, while the latter incorporates motivation, curiosity, and meaningfulness in learning new things. Second, for the cognitive dimension, ALC design could shift from the perspective of a "knowledge expert" to a "maker." The former emphasizes a high level of subject-specific knowledge, while the latter focuses on innovation, outcomes, and producing new things through social interaction strategies, such as observation, imitation, and public demonstration. Third, for the behavioral dimension, ALC design could extend student behaviors from short-term participation to long-term habit formation. The former is viewed as a task to be completed, while the latter involves activities that are done regularly to improve oneself and develop an active and growth mindset.

Research issue #3. What are the educational roles and strategies of ALCs?

Unlike intelligent tutoring systems (ITSs), ALCs simulate peers whose competence might be equal, or weaker than that of human students. ALCs are not designed to serve as "tutors" who with expert domain knowledge (Chou et al., 2003; Johnson et al., 2000; Lester et al., 1999). In other words, ALCs might feel confused or make mistakes while learning a new topic, or solving a new problem. However, ALCs offer social scaffolding and a learning context in which human students have more opportunities to interact with ALCs and hence learn more and better, as suggested by the zone of proximal development. ALCs are generally regarded as artificial characters with human-like characteristics, either virtual or robotic, designed to play specific educational role for promoting student learning in a social learning environment. Significant educational roles of ALCs are described as follows:

Collaborators: Learning by collaboration

ALCs provide social scaffolding to interact with students, enriching their learning environment through more artificial participants. ALCs do not assume the role of experts. Instead, their non-authoritative roles attract students to interact with them in various ways. For example, "Lucy", an ALC plays the role of a "collaborator" to encourage students to converse and articulate their thought (Goodman et al., 1998). Through limited and pre-designed conversation channels, ALCs motivate students to reflect what they learn. Another example is "Learning companion agents," which offers ALCs with varying competences (both strong and weak ones) to interact and collaborate with students in solving elementary mathematics (Hietala & Niemirepo, 1998). Findings indicate that maintaining student interest in learning requires special attention to the personal characteristics of the ALCs, such as different appearances, competences, and persona.

Competitors: Learning by competition

In addition to acting as collaborators, ALCs can also take on the role of "competitors" to interact with students. Competition provides students with a clear and immediate goal to strive for, while a competitive ALC fuels their motivation to engage in learning. In other words, in a competitive environment, ALCs act as "motivators" to keep students interested in learning. Thus, while ALCs play the role of "competitors", they are often involved in game-based learning or gamification settings. For instance, the "distributed WEST" system provides learning activity models within a gaming environment, based on various combinations of actors (which may be students or ALCs) and facets such as roles, numbers, and capability levels of ALCs (Chan et al., 1992). Another example is the "Joyce" system, which features multiple ALCs as virtual agents competing with students in a synchronous quiz game environment (Chang et al., 2003). In addition, a "trouble maker" might be a special role where ALCs interact with students in a competitive environment (Aimeur & Frasson, 1996). The purpose of the trouble maker is to propose different perspectives or difficult problems to challenge students by "learning by disturbing" strategy, providing more opportunities for learning and reflection (Aimeur et al., 1997).

Tutees: Learning by teaching

ALCs can play the role of tutees to engage students in learning by teaching (Chan & Baskin, 1988). Teaching ALCs stimulates many effective learning activities.

(1) Learning with the expectation of later teaching

Studies have shown that students who are told they will teach other students after learning, even if they do not actually teach (i.e., only expect to teach), perform better than those who do not have this expectation (Bargh & Schul, 1980; Fiorella & Mayer, 2013). The expectation of teaching increases students' motivation and attention, leading to better learning outcomes.

(2) Learning by preparing for teaching

Asking students to construct teaching notes and content helps them organize and consolidate the knowledge they have learned (Ching et al., 2005).

(3) Learning by modeling or demonstrating learning tasks

Students can be asked to model or demonstrate learning tasks to teach ALCs. This approach makes students' knowledge visible and inspectable, helping them reflect on and refine their understanding. If students cannot demonstrate learning tasks correctly, they need to review the content. For example, the DENISE system requires students to teach by constructing a causal qualitative model of economics (Nichols, 1994), while the Betty's Brain system asks students to teach by creating and debugging a concept map to model their knowledge (Biswas et al., 2005; Leelawong & Biswas, 2008).

(4) Learning by explaining to others and answering questions

Studies have shown that students benefit from explaining knowledge to others (Fiorella & Mayer, 2013; Kobayashi, 2019; Ploetzner et al., 1999). When explaining to tutees, students must address their questions by providing further explanations, clarifications, or examples (Kobayashi, 2019). This process engages students in knowledge-building activities, including monitoring, integrating, elaborating, repairing, and revising their knowledge (Roscoe & Chi, 2007). Deeper questions from tutees can enhance student tutors' reflective knowledge-building explanations, so ALCs can be designed to prompt deeper questions (Roscoe & Chi, 2008).

(5) Learning by tutoring

When ALCs perform learning tasks, students can learn by tutoring them, including diagnosing and correcting errors, and helping ALCs complete the tasks (Chan & Chou, 1997; Chou et al., 2002; Uresti & Du Boulay, 2004). ALCs can be designed to perform poorly or to make specific errors that students need to address.

(6) Learning by reflection during teaching

When students are unable to explain content or answer tutees' questions, they may reflect on and identify their knowledge gaps, which can promote re-study of the material (Ching et al., 2005).

Negotiators: Learning by negotiation

During learning, students require various self-regulated learning skills, such as self-assessment, goal-setting, monitoring, regulation, and help-seeking (Panadero, 2017; Winne, 2011; Zimmerman, 1990; Zimmerman et al., 1996). However, some studies show that students often exhibit poor self-regulated learning behaviors, such as overestimated self-assessments, inappropriate goal-setting, lack of regulation, and avoidant help-seeking, which can lead to poor learning performance (e.g., Chen et al., 2019; Chou et al., 2015; 2018; Chou & Zou, 2020; Winne, 1996; Zimmerman & Schunk, 1989).

ALCs can act as negotiators to engage students in learning through negotiation, particularly focusing on self-regulated learning. By interacting with ALCs, students receive scaffolding that enhances their self-regulated learning skills and helps them regulate poor self-regulated learning behaviors (Chou et al., 2015, 2018). For example, students can negotiate with ALCs to assess their mastery levels of content. Both students and ALCs evaluate the students' mastery levels, with the ALCs providing external feedback to encourage reflection and improvement (Chou & Zou, 2020). If there is a discrepancy between the assessments of students and ALCs, students negotiate with the ALCs to resolve it. ALCs can be designed with various negotiation strategies to regulate poor self-regulated learning behaviors (Chou & Chang, 2021). Studies have demonstrated that negotiation with ALCs can improve students' self-regulated learning behaviors and performance. These improvements include enhanced self-assessment and content decision-making (Chou et al., 2015), better goal-setting (Chen et al., 2019), and more effective help-seeking behaviors (Chou & Chang, 2021; Chou et al., 2018).

Animal companions: Learning by nurturing

Animal companions are animal-like or pet-like ALCs designed to enhance students' interest and long-term motivation. They use a "reciprocal caring" approach, where students nurture their ALCs daily, and in return, ALCs remind students of their learning status (Chen, 2012). These ALCs act as "pets" or "playmates," fostering a pet-human relationship that sustains students' long-term motivation (Al Hakim et al., 2023). Often, animal companions are incorporated with game-based learning strategy, and benefit students' learning in four aspects including effort-making (Chen et al., 2007), goal-pursuing (Chen et al., 2012), team-collaboration (Chen et al., 2007), and self-reflection (Chen et al., 2007). The four aspects are described as follows:

First, effort-making. Students' behaviors are affected by perceived causes of achievement, and effort is a factor that they can control (Weiner, 1985, 1992). Thus, students should be encouraged and guided to attribute their outcomes to their own effort or lack thereof. Not all students realize the importance of effort (Seligman, 1994) or believe that they can change their learning beliefs (Dweck, 2000). Therefore, animal companions can bridge the gap between effort-making and achievement by encouraging students to focus on effort as a key to success.

Next, goal-pursuing. Animal companions set challenging quests in the game world, which gives students a sense of control and responsibility. The presence of animal companions also fosters a social commitment to achieving goals, rather than merely focusing on their individual goal. This approach helps students fell more in control and responsible, and the social commitment aspect of having an animal companion provides commitment and motivation for goal-pursuit.

Third, team-collaboration. Animal companions introduce a competitive element within team-based games. For instance, systems like My-Pet and Our-Pet show individual and team goals, respectively (Chen et al., 2007). The team competition in Our-Pet encourages students to improve team performance and develop positive team relationships, thereby enhancing member interdependence. To win group competitions, individual students must also perform well, promoting individual accountability alongside member interdependence. Thus, animal companions foster key elements for team works: individual accountability and member interdependence.

Finally, self-reflection. ALCs also play the role of "reflectors," promoting students' self-knowledge and reflection through the learning strategy of the "open student model" (Chen et al., 2007). An "open" student model means making the content of the student model visible and accessible to students, rather than hiding it within the system as an internal component. Animal companions can bring promising gains by serving as open student model to help students plan learning goals, improve communication between students and systems, and act as a scaffolding tool to self-assessment (Bull, 2004; Bull & Nghiem, 2002; Chou & Zou, 2020).

Research issue #4. What are the expected outcomes and related evaluations of ALCs?

Assessing ALCs is crucial for understanding their efficacy and impact on learning. The expected outcomes can be broadly categorized into cognitive, meta-cognitive, affective, behavioral, social, and wellbeing dimensions, each with its own evaluation criteria.

Cognitive outcomes

At the cognitive level, ALCs aim to improve understanding, retention, and application of knowledge (Castro-Alonso et al., 2021; Lusk & Atkinson, 2007; Moreno et al., 2001). For instance, Kochmar et al. (2022) propose a machine learning approach to automatically generate personalized feedback in intelligent tutoring systems, improving student performance outcomes. Systems like Cognitive Tutor (Koedinger et al., 1997) demonstrate significant cognitive gains. Quantifiable metrics such as test scores, task completion rates, and error reduction are employed to gauge efficacy (Kim et al., 2006). Researchers may use experimental designs comparing ALC-assisted learning with traditional methods to quantify cognitive gains.

Meta-cognitive outcomes

Meta-cognitive outcomes focus on learners' abilities to regulate their learning processes, such as Betty's Brain (Biswas et al., 2016). ALCs can be designed to foster skills like self-monitoring (Chou & Zou, 2020), goal-setting (Harley et al., 2018), self-regulation (Karaoğlan Yılmaz et al., 2018), critical judgment (Aprin et al., 2024), and strategic planning (Arroyo et al., 2014). Instruments like self-reported questionnaires and learning analytics can evaluate the meta-cognitive benefits imparted by ALCs.

Affective outcomes

Affective outcomes measure the emotional and attitudinal impacts of ALCs (Burleson, 2006). Factors like engagement, motivation, and learner satisfaction fall under this category, exemplified by animal companions (Chen et al., 2011). Surveys, interviews, and real-time emotional tracking technologies can provide insights into these affective dimensions.

Behavioral outcomes

Behavioral outcomes pertain to tangible actions or practices resulting from interaction with ALCs, as demonstrated by AutoTutor (Graesser et al., 2005). This could include time spent on learning tasks, frequency of interaction with ALCs, and adoption of recommended strategies (McQuiggan & Lester, 2007). Observational methods and user activity logs can serve as valuable data sources for behavioral evaluation.

Social outcomes

ALCs can also impact the social dynamics of learning, particularly in collaborative settings. Metrics here might include the quality of peer interactions, social engagement, and community building (Kim & Baylor, 2006). Qualitative methods like focus groups or social network analysis could be employed to assess these social impacts.

Wellbeing outcomes

The holistic wellbeing of learners is increasingly considered an important outcome (McQuiggan & Lester, 2007). This includes aspects like stress reduction, work-life balance, and overall life satisfaction. Psychometric tests and wellbeing scales can offer quantitative measures, while qualitative interviews provide nuanced insights.

In summary, the expected outcomes and related evaluations of ALCs are multi-dimensional, covering cognitive, meta-cognitive, affective, behavioral, social, and wellbeing aspects. A multi-method approach combining quantitative and qualitative techniques can offer a comprehensive understanding of the ALCs' efficacy and areas for future improvement. By employing diverse evaluation methods, educators and researchers can gain a deeper understanding and insights into the ways ALCs contribute to the students' learning experience.

ALCs in specific subject matters: Some examples of pedagogical design

This section presents pedagogical designs using ALCs in some subject matters, including science, social science, English as a second language (ESL), reading, writing, mathematics, and computational thinking.

Science

“Inquiry” has consistently been the heart of science education. Recent science education reforms have deepened the teaching and learning of inquiry, and have placed a strong emphasis on engaging learners in both minds-on and hands-on activities like scientists throughout the inquiry process. Accordingly, some inquiry instructional approaches have been proposed to support students’ inquiry learning. Undoubtedly, ALCs possess great potential for facilitating learners’ inquiry process and outcomes. ALCs can be designed to take on various roles, such as peer tutors, tutees, collaborators, competitors and facilitators. However, the design and use of ALCs should align with inquiry teaching approaches. For example, the Question-Initiation-Driven Inquiry (QIDI) approach emphasizes the pivotal role of students’ question initiation driven by observation and curiosity. QIDI involves a continuous and progressive inquiry process encompassing six phases: student question initiation by triggering curiosity, inquiry questions confirmation, answers and explanations inquiry, core-concept-focused knowledge integration, follow-up questions initiation, and further investigation with science projects (Looi et al., 2023). ALCs could support QIDI learning in three aspects:

(1) Thinking tools

Rather than merely serving as the provider of “correct answers” or information, ALCs can serve as “thinking tools” for scaffolding students’ various “minds-on” activities across different QIDI phases, such as comprehending scientific literature, formulating questions, constructing explanations, generating arguments, and proofing reports.

(2) Cultural vehicles

From anthropological viewpoint for science education, teaching science is viewed as “cultural transmission”, and learning science as “culture acquisition” (Cobern & Aikenhead, 1997). ALCs could be designed as cultural vehicles that interact with learners to transmit “culture of science.” This encompasses the use of scientific language, social interaction norms, and share values within the science community.

(3) Reflective portfolio

ALCs can accompany students throughout their inquiry learning journey and serve as data collectors for reflective portfolios. They can capture insights into students’ cognitive, metacognitive, and emotional aspects of inquiry learning. Utilizing learning analytics techniques, these accumulated data can unveil the trajectory of students’ learning progress over time.

Social science

ALCs have the potential to revolutionize instructional design in social science teaching and learning by offering innovative solutions that can fundamentally change how curricula are developed and how students engage with the subject matter. Rather than merely serving as repositories of vast real data, one of the most impactful roles ALCs can serve in social science education is facilitating collaborative problem-solving. ALCs can act as partners while students are tackling complex social issues and practice-based projects. They can bring insights, enrich perspectives, suggest strategies for actions, and search for better solutions.

With the advent of generative AI, we can leverage insights from its perspective to inform our own understanding and utilize its extensive power as knowledge repository to shape the future collaboratively. A dedicated generative AI system could be developed to serve as a strategic companion in issue-based learning games, thereby enhancing the educational experience. In this role, ALCs function as consultants, providing insights for decision-making, suggesting possible strategic approaches to solve conflicts, and offering psychological support as students navigate complex scenarios and make strategic decisions within their assigned roles. Students seek advice from their AI consultant in the game for extra historical content, scenario references, and strategic advice to inform decision-making in group work scenario. In this process, students learn to ask pertinent questions, issue effective commands, validate the correctness of resources, and utilize information appropriately.

In addition, ALCs can also function as tutors, tutees, or partners, tailoring learning experiences to individual needs and preferences. Through interactions with ALCs, students deepen their understanding of social science concepts by seeking explanations, guidance, or engaging in simulated debates. ALCs provide continuous feedback to students by monitoring student progress, identifying challenging areas they are struggling with, and offering real-time assistance. This feedback loop enables both teachers and students to recognize strengths and weaknesses, successes and failures, facilitating intervention and improvement. Therefore, the learning process remains dynamic and responsive, forming the unique journey of their own.

ESL

English conversation practice is a critical skill for ESL learners. However, English conversation practice is not easy to implement in the classroom. Traditionally, English conversion practice is conducted face-to-face, which is inconvenient and costly for both learners and teachers. In addition, managing simultaneous conversation practice with multiple students in the traditional classroom settings presents challenges.

Although technology enhanced language learning (TELL) and computer-mediated communication (CMC) technology attempted to address these issues by allowing learners to practice English conversation over the Internet, these methods still face hurdles such as difficulty in matching two or more learners, high costs, and inadequate learning materials to supplement online English conversation activities, etc. The development of ALCs provides a promising opportunity to solve these challenges.

For the acquisition of conversational skills, learners can communicate with other English speakers or ALCs, actively participate in discussions, express their ideas, and understand the perspectives of others. By interacting with ALCs, learners can practice vocabulary, grammar, and pronunciation to improve memory and language development.

Advancement in technology, particularly seamless computing, speech recognition and synthesis, and generative AI provide a robust foundation for developing English conversation ALCs. These ALCs, combining speech recognition and speech synthesis with generative AI and student modeling, have the potential to create a 24/7 environment for English conversation practice, enhancing accessibility and convenience for learners. The ALCs will be able to understand learners' English conversational ability and provide English conversational opportunities for the learners through learning materials generated by the generative AI. The development of ALCs holds the potential transform English conversion practice by offering a continuous learning environment that adapts to learners' abilities and provides ample opportunities for practicing conversational English.

Reading

Developing ALCs for children's reading presents unique design challenges and opportunities. The primary goal is to stimulate reading interest, facilitate discussions, and encourage sharing of book content, particularly across different fields of literature.

One of the main design objectives is to provide interest and knowledge support through comments generated by the ALCs as the child reads. These comments must be contextually relevant, informative, and engaging (Cagiltay et al., 2022). Recent research has explored user preferences for different interaction modalities, such as text-based comments, voice responses, or animated expressions. Understanding these preferences is crucial for enhancing the quality and appeal of the interactions.

The emotional dimension of the ALCs' responses significantly impacts a child's connection with the companion. Designing comments that align with the ALCs' simulated emotions can offer a more immersive and relatable experience. For instance, an ALC displaying excitement when a child reaches a thrilling part of the book can enhance engagement and situational interest (Yueh et al., 2020). This emotional coupling helps children feel more connected to the ALC, making the reading experience more enjoyable and interactive.

Beyond generating comments and providing emotional support, ALCs can engage children in deep book discussions, asking questions and prompting them to think and share about the book's content. Such interactions enhance comprehension and foster critical thinking and expression skills. When children discuss reading with an ALC, they are more likely to develop a deeper understanding and sustained interest in the book's content (Liu et al., 2024).

The long-term deployment of ALCs, especially in home settings, brings additional challenges. Sustained interaction over several weeks necessitates that ALCs remain adaptable and continually engaging. Ongoing research investigates how "interest support comments" can maintain children's situational interest in reading materials over extended periods. Additionally, the impact of long-term deployment on children's reading patterns and interests is an area ripe for exploration (Xu et al., 2022).

In summary, the design of ALCs for children's reading must consider interaction modalities, emotional coupling, the promotion of book discussions and sharing, and the dynamics of long-term engagement. Addressing these factors collectively can contribute to a more effective and enriching reading experience, meeting the aim of increasing reading interest, facilitating discussions, and encouraging the sharing of book content.

Writing

ALCs play a substantial role in integrating strategies that enhance writing skills and develop interest in writing. These strategies not only foster a supportive and engaging writing environment but also create a space where students feel comfortable and inspired to express their ideas, vibrantly and creatively. By offering personalized feedback, guiding students through various writing processes, and providing inspiration through diverse ideas and concepts, ALCs can create a comprehensive and dynamic writing experience in which students can thrive (Lin & Chang, 2020; Wambsganss et al., 2024).

The design of ALCs for writing includes several structured approaches to fostering various aspects of writing (Looi et al., 2023):

(1) Writing-habitually

This approach focuses on establishing a writing habit through daily practice. By cultivating this habit, students will write frequently, ideally becoming competent writers in various domains. In this approach, students select their individual themes and read related articles to inspire their writing. They then integrate new knowledge from those articles with their own personal views when writing about the themes. This process helps students better understand theme-based articles and develop ideas. ALCs, in this approach, can offer more ideas and concepts adaptive to students' needs, enabling them to explore different perspectives. This enriches their writing and enhances their ability to think critically and innovatively (Liao, 2023a).

(2) Writing-curiously

This approach aims to foster students' curiosity about the topic they are studying through the practice of question generation. Students first read articles related to the topic, engage in group discussions, and then explore various perspectives by asking questions about the articles they have read. Based on ideas from these questions, individual students begin their own writing. At this stage, ALCs analyze students' writing and pose additional questions, prompting students to consider more viewpoints in their writing (Hung & Liao, 2023; Lee et al., 2024). Besides helping students develop interest in the topic they are writing about, this approach enables students to think critically by considering multiple perspectives.

(3) Writing-better-and-better

Inspired by Hemingway's famous statement—'The only kind of writing is rewriting'—this approach emphasizes the significance of revision. Students, based on peer feedback and self-examination, are encouraged to progressively improve the quality of their writing through repeated revisions of their drafts. In the revision process, ALCs play a substantial role by providing ongoing and individualized feedback, guiding students to discover mistakes, identifying areas for further improvement, and suggesting directions for enhancement (Liao, 2023b; Wang et al., 2024). Subsequently, teachers engage in discussions with students about the ALCs' feedback and evaluate these insights. This iterative process cultivates a sense of ownership and connection to their work. Additionally, this approach empowers educators, integrating them into the students' writing development.

(4) Writing-longer-and-longer

This approach challenges students to write novels over an extended period. Through this process, students build their confidence and identity as writers, instilling a sense of pride and accomplishment. Meanwhile, ALCs assist students in gathering information and organizing their notes for these novel writing projects, ensuring they have a structured plan and the necessary resources (Liao & Tu, 2024). These long-term writing projects demonstrate students' ability to accomplish significant writing tasks, nurturing them as lifelong creators of ideas and imaginations, leaving them with a sense of pride, and motivating them to continue their writing journey.

In summary, ALCs support students' writing development by providing personalized feedback, cultivating consistent writing habits, identifying areas for improvement, and revising drafts repeatedly. They also encourage deeper and more substantial engagement, such as writing novels. By integrating structured approaches such as writing habitually, writing with curiosity, striving for continuous improvement, and tackling longer writing tasks, ALCs help students build strong writing skills, develop critical thinking, and nurture a lifelong interest in writing. The comprehensive support offered by ALCs ensures that students improve their writing abilities and find joy and fulfillment in the creative process.

Mathematics

ALCs can play a variety of roles in mathematics education, such as tutors, coaches, experts and lifelong learning partners. One of the most influential roles of ALCs in this field is facilitating individualized and adaptive learning (Arroyo et al., 2014; Chou et al., 2002). As students tackle complex mathematical problems and engage in practice-based projects, ALCs can act as personalized tutors, providing tailored insights and suggesting strategies for problem-solving that enrich students' understanding that leads to more effective solutions. This individualized approach helps to enhance students' critical thinking and problem-solving skills with the aid of ALCs (Shamir et al., 2008). ALCs can adapt to each student's learning process and style, ensuring a thorough and in-depth understanding of topics before progressing to more advanced topics, thereby making the learning experience more engaging and effective.

In the learning activities designed for students to learn mathematics, ALCs offer customized learning experiences based on a student's progress and comprehension level. This facilitates learning as an individual pace, ensuring a thorough understanding of each concept. When solving mathematical problems, ALCs can provide immediate feedback and detailed explanations when students encounter difficulties. Moreover, ALCs tailor practice problems to match a student's ability and progress, challenging them appropriately without causing frustration. ALCs serve as an extensive repository of mathematical resources ranging from basic to advanced topics, including problem-solving strategies, video tutorials, and interactive questions. In collaborative learning environments, ALCs can act as tutors or teachers, helping and facilitating collaboration among students. Furthermore, ALCs can collect and analyze student learning data, aiding teachers in understanding student performance and adapting teaching strategies accordingly. By providing data-driven insights, ALCs help teachers identify areas where students may need extra support and adjust their teaching methods to better meet individual needs.

In brief, ALCs bring innovation and improvement to mathematics education by offering personalized and adaptive learning, fostering active student engagement, and supporting teachers through data-driven approaches. This comprehensive ALCs support system ensures that students receive the guidance they need while enhancing the overall teaching and learning experience.

Computational thinking

Through interaction with students, ALCs are reshaping computational thinking education by offering personalized support and creative approaches, enhancing their grasp of core computational ideas. Beyond mere guidance, this human-AI collaboration provides a flexible and active learning environment.

Computational thinking involves breaking down problems, recognizing patterns, abstracting details, creating algorithms, evaluating solutions, and automating tasks. ALCs can effectively offer support for learning these six components:

(1) Decomposition

ALCs simplify complex problems into manageable tasks, offering advice and examples to aid understanding. Deconstructing problems into manageable steps, ALCs makes each part understandable and solvable. For instance, during a coding task, an ALC can delineate the essential steps for resolution, offering guidance and milestones throughout the process.

(2) Pattern recognition

ALCs identify and emphasize patterns supported by targeted exercises and quizzes to reinforce learning. Based on recognized patterns, ALCs enhance students' prediction ability. For instance, ALCs can incorporate pattern recognition exercises within the coding curriculum, showing how certain programming constructs are common in different contexts, thereby enhancing comprehension through consistent engagement.

(3) Abstraction

ALCs provide students simplification exercises and relevant scenarios, through which they can learn to extract key elements of a problem. This approach helps students in developing models with wide-ranging applicability. By presenting simulations of actual challenges, ALCs guide students to distill essential information and forge resolutions, while offering pertinent feedback and assistance.

(4) Algorithms

ALCs assist creation and understanding of algorithms by offering templates, examples, and code walkthroughs. Such assistance can guide learners in formulating step-by-step procedures to tackle issues. For instant, ALCs may aid a student in devising a data sorting algorithm, offering prompt responses on its efficacy and accuracy.

(5) Evaluation

ALCs can provide critiques for improvement and offer test cases to assess algorithms, teaching students debugging and optimization skills. By testing algorithms and providing detailed analysis, ALCs validate students' comprehension of their solutions' performance. For instance, an ALC may critique a student's game code to enhance functionality and remove glitches.

(6) Automation

ALCs encourage students to build skills in process automation by suggesting helpful tools and supporting project development. Such experiences not only improve technical abilities but also show how computational thinking can be applied in daily activities. ALCs can assist a learner in automating tasks related to data analysis and offer detailed guidance and examples that underscore the benefits of automation.

Overall, ALCs enhance students' computational thinking skills by using methods like coding sessions, complex problem-solving, and customized quizzes. By offering individualized teaching, specific feedback, and interactive activities, ALCs boost computational thinking through personalized instruction, detailed feedback, and interactive experiences, leveraging AI to engage students, assist in developing their computational skills, and prepare them for the upcoming Seamless AI World (as described in the section below).

A grand challenge for humanity: The General Artificial Companions Hypothesis

The world is on the brink of peril. We are confronting unparalleled challenges, including millions of deaths caused by COVID-19, climate change, resource depletion, environmental pollution, wealth disparities, and worries over AI's negative impact on humanity. Furthermore, escalating global conflicts intensify fears of a potential nuclear apocalypse. Resolving such human crises fundamentally hinges on education playing a critical role, and ALCs must extend their objectives beyond supporting learning.

If we disregard the differences between religion doctrines and philosophical or political ideologies, and simply ask most individuals what they aspire to in their lives, it is highly probable that they will mention happiness, health, wealth, and achievement, among other things. If we ask for more, such as what one strives for beyond themselves, it is likely they will talk about nurturing their families, maintaining positive relationships with friends, and contributing to making society and the world a better place.

Speaking of what constitute a good life that one aspires to, we naturally associate them with humanistic psychologist Maslow's hierarchy of needs (physiological, safety, love and belongingness, esteem, self-actualization) (Maslow, 1943) and positive psychologist Seligman’s model of flourishing, PERMA (positive emotions, engagement, positive relationships, meaning, and achievement) (Seligman, 2011). If wellbeing is defined as a holistic measure of physical, mental, and social health, indicating an individual’s happiness, life satisfaction, and the ability to function effectively, then both Maslow and Seligman’s frameworks fall within the realm of wellbeing. Yet, we all live on the same planet and wish for everyone around the globe to enjoy wellbeing in their lives too. We refer to this as ‘global wellbeing,’ a goal to which everyone should try to contribute.

However, the pursuit of individual wellbeing alone does not suffice. Emphasizing harmony, or positive relationships, with the people and environment around us is crucial. The Cambridge Dictionary defines harmony as ‘a situation in which people are peaceful and agree with each other, or when things seem right or suitable together.’ In our context, harmony encompasses ‘environmental harmony’ and ‘humanity harmony.’ Environmental harmony deals with issues such as global warming, natural disasters, pollution, earth resource exhaustion, and the extinction of species. Humanity harmony consists of four levels: individual harmony, which involves inner peace, balance, coherence, satisfaction, and so forth; family harmony, which refers to love, care, nurturing, parental respect, and so on among family members; societal harmony, which describes compassion, equity, diversity, inclusiveness, collaboration, integrity, and the like, for both acquaintances and strangers in society; and global harmony, which again involves compassion, equity, diversity, inclusiveness, collaboration, integrity, etc., but among different societies and states. Indeed, the Sustainable Development Goals (SDGs), along with UNESCO’s global citizenship initiatives and the OECD’s global competence frameworks, align with this concept of harmony. Furthermore, in recent years, UNESCO has released documents focusing on wellbeing and harmony in education.

It is worth noting that harmony is a necessary condition for individual wellbeing: without global harmony, societal harmony cannot be maintained; without societal harmony, family harmony cannot be achieved; and without family harmony, individual wellbeing is impossible. Therefore, societal and global harmony must become common and salient values for everyone in the world, since taking care of oneself and one’s family is an innate instinct already.

Given the aforementioned deliberations, ‘Global Harwell’—where the term ‘Harwell’ combines ‘harmony’ and ‘wellbeing’—on one hand, represents what humankind aspires to (Chan, 2023; Global Harwell Group, 2024a). On the other hand, it refers to a set of overarching values or a collective ethos that defines societal norms, ethics, and goals on a global scale. This suggests that the pursuit of Global Harwell should be established as the core and basic values for humanity, indicating that the very purpose of human knowledge and technology is to support the achievement of Global Harwell. Also, since the education of our next generations determines the destiny of our future world, Global Harwell should be adopted as a shared, fundamental global educational goal.

From learning to the pursuit of Global Harwell in the Seamless AI World

In the Seamless AI World (SAIW) (Global Harwell Group, 2024b), where almost everything is seamlessly connected while being filled with and empowered by AI technology, our world is 'shrinking' or becoming 'smaller' in the sense that individuals who are physically far apart can easily and closely interact in their native languages through AI-supported instant interpretation. The exchange of ideas among students from different places and cultures is expected to significantly increase.

Obviously, in the SAIW, there will be numerous artificial companions around. Challenging yet urgent, artificial companions play a crucial role not only in assisting with learning but also in pursuing the Global Harwell goal. Thus, if researchers and educators across the globe collaborate, and if Global Harwell is adopted as a global educational goal, we can anticipate a profound transformation in education.

However, involving many aspects of learning, such endeavor brings forth a set of challenges in the SAIW:

(1) Where and when to learn in the SAIW?

(2) With whom should the student learn, such as human teachers, classmates, or artificial companions in the SAIW?

(3) Will there be a theory that informs the design of artificial companions for learning, as well as for attaining the Global Harwell goal in the SAIW?

(4) What knowledge and skills should students acquire about Global Harwell, and how can such knowledge and skills be integrated into their subject matters in the SAIW?

Lifelong artificial companions

If we predict there will be numerous artificial companions around us, then the advent of lifelong artificial companions for individuals is within reach. Chan et al. (2001, p. 159) described a dream: "… every student in the future has a set of lifelong learning companions. For a youngster, s/he may choose a set of 'animal' companions, and in her/his school years, s/he will be like a leading character in a Disney cartoon movie always surrounded by the companions. Every animal companion can assume a different role. For example, a dalmatian is a collaborator. Mushu dragon is a peer tutor. Monkey king is a troublemaker, who challenges the student from time to time. Tamagochi (a once popular electronic chick that can be incubated by kids) can be taught by the student to play against the other Tamagochies raised by other students in some network learning games. In other words, we can 'disneyficate' the learning environment." For the creation of a lifelong learning companion, Chou et al. (2003, p. 266) further elaborated that "Such a learning companion is like a friend that stays with the student from childhood to adulthood. The companion stores the student's lifelong portfolio. Educational agents constructed in many domains can be combined into a lifelong learning companion, or the student's lifelong portfolio can at least be exchanged among the educational agents."

Lifelong artificial companions are designed to accompany individuals throughout their lives, offering continuous support and interaction. They adapt to changing needs and preferences, providing personalized assistance, information, and even emotional companionship across various life stages— for example, during years in school, working life, and retirement. These companions aim to build long-term relationships, fulfilling roles such as personal assistants or caregivers, while respecting ethical considerations such as privacy and autonomy. By integrating deeply into daily routines, lifelong artificial companions enhance wellbeing, illustrating a future where AI technology plays a supportive and integral role in enhancing human life from childhood through old age.

Quest for Artificial General Intelligence with ethical, emotional, and sociability awareness

AI has made remarkable strides in recent years, outperforming humans in specific tasks such as medical diagnostics, natural language processing, financial trading, industrial automation, playing games, and analyzing data. However, when it comes to overall cognitive abilities and understanding the world as humans do, AI has not yet surpassed human-level intelligence. This distinction between narrow AI and Artificial General Intelligence (AGI) (or Strong AI [3]) is crucial: while narrow AI excels in specific domains, AGI aims to achieve human-like cognitive abilities across a wide range of tasks, akin to how humans think and learn. This includes capabilities such as reasoning, problem-solving, abstract thinking, and adapting to new situations.

While AI has transformative potential, its integration into society must be approached cautiously, with careful consideration of ethical implications and societal impact. This includes considerations of fairness, transparency, accountability, and the ability to make decisions that respect human autonomy and dignity.

In terms of values and attitudes, AI systems can exhibit behaviors that mimic values or attitudes, following ethical guidelines or rules that govern their interactions with humans, such as simulating empathy or politeness. However, they still lack the deeper emotional or value-based comprehension that humans possess. The challenge lies in developing AI systems that not only perform tasks effectively but also align with human values, ethical principles, and factors of emotion and sociability when interacting with humans in decision-making. Current AI systems still lack the intuitive understanding of complex human values and social nuances, as well as emotional intelligence, which are essential for navigating ethical dilemmas and interpersonal interactions in various contexts.

As AI technology continues to evolve, the quest for AGI and AI systems that are ethically, emotionally, and sociability aware remains ongoing. Achieving these goals will require interdisciplinary collaboration and continued advancements in AI research and development. The pursuit of Global Harwell, in such a situation, may serve as a beacon illuminating the path forward.

General Artificial Companions Hypothesis

Our proposition of the General Artificial Companions Hypothesis (GACH) sets forth a visionary goal for AI, envisioning its role in advancing the future world towards Global Harwell era. This hypothesis posits that AI, when developed with a focus on human-AI companionship and societal betterment, can profoundly impact our global community in the forthcoming SAIW. By fostering AI technologies that prioritize ethical companionship and contribute positively to societal progress, we strive not only to enhance human harmony and wellbeing but also to cultivate a harmonious coexistence between technology and humanity. Ultimately, our vision is to harness AI's potential to create a future where innovation, empathy, and sustainable development define our collective journey towards Global Harwell.

General Artificial Companions (GACs) refer to lifelong artificial companions for individual humans, powered by either AGI technology or technology nearing AGI capabilities. Additionally, all the 'overarching goals' of human-AI companionships, defined by their roles at various stages of the human actor's life, must include Global Harwell as a primary subgoal.

> *The General Artificial Companions Hypothesis (GACH) posits that within the context of SAIW, the support provided by human individuals' GACs will contribute 50% or more to the development of Global Harwell as their primary value and life goal, as evidenced by their daily behaviors.*

To elucidate, the GACH suggests that in a future scenario where Strong AI and GACs are prevalent and deeply integrated into society (SAIW), GACs will provide substantial and noteworthy support to human individuals. This support is expected not only to influence but to shape the development of Global Harwell as their primary values in lives.

According to the GACH, the contribution of these GACs to the formation of these values is substantial, potentially constituting 50% or more of the factors that influence how individuals prioritize and manifest these values in their daily lives. This influence is observable through the behaviors and interactions of individuals with their GACs.

In essence, the GACH implies that as artificial companions become more integrated and sophisticated, they will play a crucial role in shaping human values and behaviors within the framework of Global Harwell, reflecting a symbiotic relationship where technology not only assists but actively participates in the cultural and ethical evolution of society.

It is also pertinent, important, and imperative to highlight that as more people adopt Global Harwell as their life values, fewer people, out of individual or institutional selfishness, or even unconsciously, will use AI for detrimental purposes against humankind. This will, at the very least, impose more social constraints on those who seek to develop AI-empowered entities harmful to society (Liu, 2024).

Moreover, it is worth noting that the creation of GACs commences with human involvement and education because GACs can only be devised by Global Harwellians [4]—individuals who place Global Harwell at the core of their values and life aspirations. However, these Global Harwellians grow via human nurturing before validating the hypothesis. Upon successfully building GACs, the Global Harwellness—the quality or state of Global Harwell—of humans and GACs will mutually elevate through their companionship. No matter how this symbiotic relationship evolves, education is the key to ushering in a Global Harwell era.

Clearly, there are numerous issues to clarify and questions to answer regarding this hypothesis. For example, to what extent can we qualify our world as a SAIW? Can we limit the scope of a world to a well-defined community during an experiment, such as within a family, a group of families, a school including students' parents, company staff, occupational unions, and so on? If this hypothesis can be proven within such a limited scope, could it serve as a model and be rapidly disseminated worldwide? At what stage of life is it more feasible to cultivate Global Harwell, considering how individuals' values affect their life goals? All these and other issues and questions need to be addressed by researchers and practitioners adopting AI in any aspect of our human lives.

In sum, the proposal for the GACH aims to offer researchers and practitioners a goal for creating an everlasting and peaceful world with AI technology—ensuring that our future generations thrive on this planet and continue to grow in a Global Harwell future. The world, however, cannot passively await the advent of Global Harwell; our future generations' education cannot hinge on the eventual arrival of GACs. We must act now, collectively and collaboratively!

Undoubtedly, Global Harwell represents the paramount goal of AI technology for humanity!

Conclusion

Intelligent, caring, and patient, artificial companions—whether virtual or robotic, are designed to provide around-the-clock companionship to human beings. They establish positive and meaningful relationships with humans through human-like interactions, aiming to fulfill the overarching goals of these relationships. This paper highlights several key aspects of artificial companions, intending to provide broad understanding of their potentials and challenges. First, beyond supporting learning, human-AI companionship involves the interaction process between a human and an AI actor, incorporating ethical considerations, fostering engagement, and advancing holistic development. Second, a research agenda for ALCs is outlined, encompassing five components of ALCs—content and domain module, student model, pedagogy module, ALCs' characteristics of ALCs and interface—and four research issues—emergent technologies, learning theories, educational roles and strategies, and expected outcomes. During the elaboration of ALCs' research agenda, past research is reviewed, and their current capabilities and potential improvements are evaluated. Third, the design of ALCs for various subject matters, including science, social science, ESL, reading, writing, mathematics, and computational thinking is discussed, highlighting tailored approaches and the unique benefits for each discipline.

ALCs hold the potential to revolutionize education by providing personalized, adaptive learning experiences that cater to individual student needs. The approach, integrating emergent AI technologies, learning theories, and educational strategies, sustains the development of effective and meaningful use in education. More importantly, in the SAIW, everything changes. Aligning with the broader goal of artificial companions to foster Global Harwell as a shared value worldwide not only promotes academic success but also enables students to achieve harmony and wellbeing. In responding to these demands—for education, for Global Harwell, and for all aspects of life—, GACs address challenging issues related to ethical and well-rounded development. While championing the pivotal role of artificial companions in cultivating a Global Harwell era in a seamless AI world, the GACH emphatically highlights the crucial need for further clarification and investigation. Designing AI means designing the future—a future that ensures our future generations continue to survive and flourish in this century and beyond.

Abbreviations

AI: Artificial Intelligence; ALC: Artificial Learning Companion; VR: Virtual Reality; AR: Augmented Reality; MR: Mixed Reality; LLM: Large Language Model; RAAG: Retrieval-Augmented Generation; RALL: Robot-Assisted Language Learning; IDC: Interest-Driven Creator; ITS: Intelligent Tutoring System; ESL: English as a Second Language; QIDI: Question-Initiation-Driven Inquiry; TELL: Technology Enhanced Language Learning; CMC: Computer-Mediated Communication; SDG: Sustainable Development Goal; SAIW: Seamless AI World; AGI: Artificial General Intelligence; GACH: General Artificial Companions Hypothesis; GAC: General Artificial Companion.

Endnotes

[1] The Second Workshop on Metaverse and Artificial Companions in Education and Society (MetaACES2022), https://www.eduhk.hk/metaaces2022NovICCE2022/index.html

[2] Learning through machine learning techniques is challenging if we adopt deep learning.

[3] We do not distinguish AGI and Strong AI in this paper.

[4] A term was coined by Meier (2024).

Acknowledgements

We would like to thank Chee-Kit Looi, Siu-Cheung Kong, Su-Luan Wong, Wenli Chen, Lung-Hsiang Wong, Weiqin Chen, Chao-Han Liu, Wei-Ling Chiang, Jon Mason, Maiga Chang, and Fu-Yun Yu. Our exchanges have been pivotal in the development of the Global Harwell concept. We also thank Su-Luan Wong for her editing contributions to parts of this paper.

Authors' contributions

Tak-Wai Chan is the corresponding author. He organized the paper's content and authored sections including the Abstract, Introduction, AI companions and AI learning companions, The origin of artificial learning companions and subsequent works, A grand challenge for humanity: The General Artificial Companions Hypothesis, and the Conclusion. He also monitored and edited the paper's content.

Chih-Yueh Chou authored sections including 'Subsequent works' in the 'The origin of artificial learning companions and subsequent works' section, Research agenda of ALCs, 'Cognitive Load Sharing' in Research Issue #2, and 'Tutees: learning by teaching' and 'Negotiators: learning by negotiation' in Research Issue #3. Additionally, he contributed to the first paragraph of the Conclusion and assisted in integrating the paper's content.

Zhi-Hong Chen authored sections including 'Interest-Driven Creator (IDC)' in Research Issue #2, 'Collaborators: learning by collaboration', 'Competitors: learning by competition', and 'Animal companions: learning by nurturing' in Research Issue #3.

Chang-Yen Liao authored sections including 'Integration of digital and robotic technologies in networked and classroom learning environments' in Research Issue #1, Research Issue #4, and 'Reading' and 'Writing' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section.

Ju-Ling Shih authored 'Social science' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section and the second paragraph of the Conclusion. She also assisted in editing the paper to enhance the quality of English.

Ying-Tien Wu authored 'Science' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section. He also assisted in proofreading the paper.

Ben Chang authored 'ESL' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section. He also assisted in proofreading the paper.

Charles Y. C. Yeh authored 'Mathematics' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section. He also assisted in proofreading the paper.

Hui-Chun Hung authored 'Computational thinking' in the 'ALCs in specific subject matters: Some examples of pedagogical design' section.

Hercy Cheng authored the 'Artificial intelligence in education' in Research Issue #1.

Authors' information

Chih-Yueh Chou is affiliated with the Department of Computer Science and Engineering, Yuan Ze University, Taiwan.

Tak-Wai Chan is affiliated with the Graduate Institute of Network Learning Technology, National Central University, Taiwan.

Zhi-Hong Chen is affiliated with the Graduate Institute of Information and Computer Education, National Taiwan Normal University, Taiwan.

Chang-Yen Liao is affiliated with the Department of Hakka Language and Social Sciences, National Central University, Taiwan.

Ju-Ling Shih is affiliated with the Graduate Institute of Network Learning Technology, National Central University, Taiwan.

Ying-Tien Wu is affiliated with the Graduate Institute of Network Learning Technology, National Central University, Taiwan.

Ben Chang is affiliated with the Graduate Institute of Learning and Instruction, National Central University, Taiwan.

Charles Y. C. Yeh is affiliated with the Graduate Institute of Network Learning Technology, National Central University, Taiwan.

Hui-Chun Hung is affiliated with the Graduate Institute of Network Learning Technology, National Central University, Taiwan.

Hercy Cheng is affiliated with the Center for General Education, Taipei Medical University, Taiwan.

Funding

Not applicable.

Availability of data and materials

Not applicable.

Declarations

Competing interests
There are no competing interests that we know of.

Author details
[1] Department of Computer Science and Engineering, Yuan Ze University, Taiwan

[2] Graduate Institute of Network Learning Technology, National Central University, Taiwan

[3] Graduate Institute of Information and Computer Education, National Taiwan Normal University, Taiwan

[4] Department of Hakka Language and Social Sciences, National Central University, Taiwan

[5] Graduate Institute of Learning and Instruction, National Central University, Taiwan

[6] Center for General Education, Taipei Medical University, Taiwan

Received: 29 March 2024 Accepted: 20 August 2024
Published online: 1 January 2025 (Online First: 22 October 2024)

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