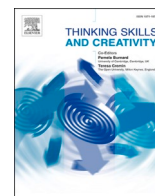


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Three-wave cross-lagged model on the correlations between critical thinking skills, self-directed learning competency and AI-assisted writing

Xiaolei Shen^a, Mark Feng Teng^{b,*}^a Faculty of Educational Studies, Universiti Putra Malaysia, Serdang Selangor, 43300, Malaysia^b Faculty of Languages and Translation, Macao Polytechnic University, Macau SAR, China

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ABSTRACT

The impact of Artificial Intelligence (AI) on English writing is gaining prominence. This study aimed to examine the interplay between critical thinking skills, self-directed learning competency, and Artificial Intelligence writing by cross-lagged model, with the focus on the moderating role of self-directed learning competency on critical thinking skills and Artificial Intelligence writing. A total of 204 participants completed a critical thinking test, self-directed learning questionnaire and a writing task. The results revealed significant correlations between critical thinking skills, self-directed learning competence, and AI-assisted writing. However, the temporal correlations between critical thinking skills and self-directed learning exhibited a reciprocal pattern over three times, while the correlations between critical thinking skills, self-directed learning, and AI-assisted writing were unidirectional. Interestingly, the findings indicated that self-directed learning moderated the relationship between critical thinking skills and AI-assisted writing over two times, but not in the third time. These findings emphasized the pivotal roles of critical thinking skills and self-directed learning in AI-assisted writing among EFL learners. They also suggested that using AI-assisted tools critically and independently in writing can mitigate the tendency to over-rely on these tools.

1. Introduction

In English language learning, writing plays a pivotal role, necessitating the skill to structure compositions effectively and articulate coherent, substantial viewpoints on specified topics. However, the restricted metacognitive awareness among learners often results in their overlooking lexical and syntactical elements, ultimately culminating in less satisfactory writing outcomes (Teng, 2016, 2019; Teng et al., 2022). Consequently, learners in a foreign language may need to foster metacognitive awareness in developing a coherent and meaningful written discourse.

Moreover, the shift of learning contexts from offline classrooms to online platforms during the COVID-19 pandemic have posed challenges regarding the advancement and the availability of technology-based tools essential for facilitating active participation in diverse learning activities (Hartwell & Aull, 2023; Segbenya et al., 2022; Song et al., 2022). Of particular concern of these challenges are the need to nurture motivation among distance learners within technology-based learning context (Kohnke et al., 2023). Therefore,

* Corresponding author.

E-mail address: markteng@mpu.edu.mo (M.F. Teng).

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educators and learners actively seek appropriate technology tools to nurture active self-directed learning competency in such learning context. Responding to this evolving landscape, the integration of Artificial Intelligence (AI) in language learning is gradually gaining traction as a potential solution.

AI represents a cutting-edge technology emulating human intelligence, offering effective solutions across diverse domains (Cope et al., 2020). The evolution of AI tools, such as *ChatGPT*, has garnered significant attention from educators and learners (Cotton et al., 2023). They are progressively integrating AI applications into their language learning pursuits, aiding learners in identifying and correcting spelling and grammar errors, specifically aiming to enhance language proficiency in compositions (Barrot, 2023; Zhao, 2022). Undoubtedly, these AI tools exert a substantial influence on writing activities, effectively mitigating learners' concerns regarding language expression and enabling them to allocate greater focus to the substantive aspects of their writing.

As AI continues to advance, understanding how to effectively and critically harness and evaluate AI-generated writing become crucial for fostering writing proficiency in individuals. Critical thinking skills as an array of cognitive strategies equip individuals with the ability to effectively select AI-assisted tools (Hartwell & Aull, 2023), and generate innovative ideas and active self-assessment (Kafri, 2022; Yin et al., 2023), particularly within the domain of writing. A substantial body of prior research supported the pivotal significance of critical thinking abilities in enabling learners to develop their own perspectives, empowering them to approach writing tasks with a heightened sense of autonomy and intellectual rigor (Dong & Chang, 2023; Lu & Xie, 2019; O'Reilly et al., 2022). Simultaneously, writers endowed with critical thinking skills have the capacity to generate concise summaries, create outlines of text, and effectively organize their thoughts (Ebadi & Rahimi, 2018). Critical thinking skills thus expand learners' perspectives and foster their development as proficient and autonomous learners, enhancing learners' self-directed learning competency (Jin & Ji, 2021).

The competence of self-directed learning grants learners to assume control over their language acquisition process, enabling them to optimize their writing skills and overall writing proficiency (Graham & Harris, 2023). Also, self-directed learning assumes a pivotal role in facilitating learners' cognitive development, especially when coupled with critical thinking skills (Garrison, 1997; Thomas et al., 2023). This combination enables learners to progress from fundamental to higher cognitive levels (Lai et al., 2022b) and thereby nurturing their cognitive abilities. By synergistically intertwining critical thinking skills and self-directed learning, learners can become adept at navigating various writing challenges, fostering creativity, and cultivating a deeper understanding of the topics they address in their writing activities (Tu, 2021; Yin et al., 2023). These studies underscored the role of critical thinking skills in self-directed learning and writing. Nevertheless, insufficient attention has been devoted to exploring the intricate interplay among critical thinking skills, self-directed learning, and AI-assisted writing in diverse writing contexts.

Therefore, the primary objective of this study was to delve into the intricate correlations between critical thinking skills, self-directed learning competency, and AI-assisted writing across diverse learning modes. By scrutinizing the interplay between these factors, the present study sought to contribute valuable insights into the design of effective writing instruction that harnesses the power of self-directed learning and AI technologies to be conducive to autonomous learning and thinking growth.

2. Literature review

2.1. AI-assisted writing

Artificial intelligence (AI) is an advanced technology that simulates human cognitive and thinking abilities across various domains to solve problems according to specific questions (Cope et al., 2020; Dwivedi et al., 2023; Kohnke et al., 2023). Currently, the awareness of utilizing AI-assisted tools in writing is raised. The function of AI can also be exploited to improve writing, such as with *ChatGPT* (Barrot, 2023; Cope et al., 2020; Kasneci et al., 2023), *Grammarly*, and *Quillbot* (Marzuki et al., 2023), which have been used to assist language learners. Some of these tools are widely utilized as problem-solving aids to generate text resembling human language, answer questions, and complete language-oriented assignments, thereby enhancing learners' performance in language tasks (Barrot, 2023; Kasneci et al., 2023). Others serve as text proofreading and revising tools, with a focus on identifying spelling and grammar errors in English text. These tools help learners recognize language inaccuracies, identify erroneous patterns, and rephrase sentences for improvement (Kohnke et al., 2023). Additionally, they offer alterations in sentence structure and synonym replacements, facilitating the preservation of original meanings and mitigating challenges related to word choice and expressions (Zhao, 2022). By harnessing these AI applications, learners adeptly surmount language proficiency challenges, ultimately refining their language performance. Artificial intelligence thus can be effectively employed as a valuable assistant technology for elevating language proficiency and refining compositions.

The advent of AI tools has assisted the writing process by immediate feedback, lexical enhancement, and logical coherence, thereby fortifying learners' language proficiency and cognitive capabilities in their writing assignments. For instance, AI tools offer learners immediate feedback, aiding in the detection of writing errors, establishing connections between prior knowledge and new information for effective self-evaluation and revision, and boosting their writing motivation (Hartwell & Aull, 2023; Kohnke et al., 2023). Moreover, the adoption of AI-assisted tools not only expands lexical range but also refines learners' writing through the logical revision of thoughts and arguments. These tools aids writers in sorting information and making inferences, effectively functioning as a cognitive aid (Barrot, 2023).

However, despite the promising usages of AI-assisted tools in writing, limitations persist. AI applications fall short in replicating human-like text, as they lack the capacity for profound thinking when it comes to expressing perspectives on a given topic (Barrot, 2023). Moreover, there is a tendency among some writers to excessively rely on AI tools without maintaining critical awareness (Hartwell & Aull, 2023). This can lead to a situation where writers prioritize the complexity of sentences over the depth and logical organization of their writing content (Marzuki et al., 2023). Therefore, although AI-assisted writing has garnered significant attention,

the integration of AI into writing demands a judicious approach, placing a specific emphasis on the pivotal role of critical thinking.

2.2. Critical thinking skills and AI-assisted writing

Critical thinking is commonly understood as a form of reflective thinking that precedes decision-making and action-taking (Dewey, 1997). It places significant emphasis on clear, purposeful, and rational thought processes (Ennis, 1992). Alternatively, it can be viewed as the process of argumentation or judgment-making (Halpern, 1998; Kuhn, 1999) involving “building a syllogistic awareness of the hierarchy of cognitive skills and taxonomies of skills” (Teng & Yue, 2023, p. 244). Much attention has been directed towards developing critical thinking skills, which are reflective of learners’ cognitive processes. These skills include inference, analysis, interpretation, evaluation, and self-regulation, all of which are fundamental in assessing one’s critical thinking abilities (Paul & Elder, 2005). The ability to make inferences and analysis enables critical thinkers to filter and assess information, thereby presenting clear perspectives for making informed judgments during the learning process (Ku, 2009). Additionally, self-regulation, which involves making adjustments based on evaluations, is particularly essential in the final stages of the thinking process. This is where critical thinkers discern strengths and weaknesses in their summarizations, enabling them to make appropriate adjustments (Li & Liu, 2021). Incorporating critical thinking skills into foreign language learning is of paramount significance, as it proves highly effective in nurturing learners’ thinking and cognitive abilities.

Nevertheless, the manifestation of critical thinking skills in AI-assisted writing is link to language proficiency. Technology-based tools like *WebQuests* (Ebadi & Rahimi, 2018) serve to enhance learners’ language proficiency by enabling them to concentrate on enriching the substance of their writing. These assisted tools are distinguished by their inquiry-based approach, making them highly effective instruments for nurturing critical thinking capability. By granting learners access to credible sources and guiding them away from inappropriate content, these tools elevate the quality of writing and contribute significantly to motivating learner engagement in writing activities. Contrarily, a survey conducted by Huang and Renandya (2018) involving 67 non-English major students revealed that *Pigai* software could not effectively support low-proficiency learners in enhancing their writing proficiency. This is due to their limited ability to detect inaccuracies in automated writing evaluations, despite harboring positive attitudes toward this feedback technology. Therefore, language proficiency is found affect learner’ using critical thinking skills in writing (Dong & Chang, 2023).

In addition to bolstering language proficiency, critical thinking skills enhance the generation of innovative perspectives and effective feedback while organizing and evaluating compositions, compensating for the lack of depth in AI-assisted writing. Learners engage in critical filtering of essential information post-AI use, enabling clear articulation of perspectives and evaluation of information from diverse sources to integrate logical arguments in language learning (Spector & Ma, 2019). For example, *Write & Improve* software acting as a feedback tool for struggling writers, effectively alleviated learners’ writing anxiety and facilitated their autonomy in self-assessment (Waer, 2021). Although these tools assists in revising language form and style, it lacks depth of thought. Critical thinking thus proves essential in AI-assisted writing, stimulating creative viewpoints during the writing process and enabling effective judgment of AI-generated feedback in the writing outcome (Barrot, 2023). However, some learners excessively depend on AI-assisted tools for essay evaluation (Kasneci et al., 2023), prioritizing text generation with these tools, leading to ethical concerns like plagiarism (Cotton et al., 2023). Consequently, using AI tools independently and effectively necessitates self-directed learning in writing performance.

2.3. Self-directed learning competency and AI-assisted writing

Self-directed learning competency encompasses an intrinsic desire to understand one’s personal characteristics, such as the persistence, and self-discipline in learning, while also flexibly employing language strategies to take the initiative in learning tasks (Zimmerman & Martinez-Pons, 1990). Additionally, some scholars viewed self-directed learning competency as a process (Garrison, 1997; Morris, 2019), “in which a learner retains control over choice and decision-making in terms of learning objectives and means” (Morris et al., 2023, p. 5). Alternatively, self-directed learning competency can be seen as a method that serves as an emotional catalyst for English learning among language learners (Voskamp et al., 2022), particularly writing (Teng et al., 2022). It entails learners actively acquiring knowledge by effectively and autonomously employing appropriate language learning strategies such as understanding and planning goals, monitoring and assessment learning outcomes (Choy & Cheung, 2022; Graham & Harris, 2023). Understanding learning objectives aids in making rational plans, while monitoring the learning process allows learners to regulate their language strategies. Ultimately, learners evaluate their learning outcomes after performing learning tasks. In addition to these theories, Garrison (1997) integrated critical awareness as a cognitive factor into self-directed learning within educational contexts including “personal characteristic, self-regulation, learning context and self-directed learning process” (p. 5). This integration delineated how individuals identify what to learn and determine approaches to achieve goals and meet task demands in specific contexts.

Self-directed learning competency is closely intertwined with technology-assisted English writing. For example, learners’ self-directed learning competency can be significantly promoted through the utilization of online auxiliary tools (Khodaei et al., 2022), such as informational communication technology integrated with online notice boards and tablets (Choy & Cheung, 2022). Moreover, unclear writing goals and a lack of recognition of one’s learning strengths may lead to a decline in enthusiasm for writing practice, thereby diminishing self-motivation for self-directed learning and potentially triggering writing-related anxiety (Tu, 2021). Thus, self-directed learners tend to formulate well-defined plans aligned with their writing objectives while efficiently harnessing various technology-assisted tools to aid them throughout the writing process (Teng & Zhang, 2024). Contrarily, many students do not view mobile technology as an effective tool because they fail to recognize its value and lack self-directed learning competency necessary for effectively utilizing technology-assisted tools to enhance their learning (Lai et al., 2022a). Notably, Lai et al. (2022a) identified

influential factors such as individual attitudes, subjective norms, and behavioral intentions, which rely on learners' autonomy and support from teachers and peers in utilizing mobile technology during the language learning process.

These studies primarily highlighted the impact of self-directed learning competency on learners' writing performance when assisted by technology-based tools, considering intrinsic cognitive and motivational factors. Drawing on these studies, this research has developed Garrison's (1997) self-directed learning theory, incorporating cognitive and affective elements such as self-management, self-monitoring, and motivation. This theory illustrates how learners assume control and engage in critical thinking to construct meaning during their learning process, as depicted in Fig. 1. Critical thinking represents the intricate cognitive processes involved in creating personal meaning and valuable knowledge through writing assignments (Garrison, 1997; Morris et al., 2023). Simultaneously, self-direction aids learners in controlling their cognitive processes by critical thinking, focusing on self-management and self-monitoring, addresses "learning goals, management of learning sources and support, facilitate the energize meaningful and continuous learning" (Garrison, 1997, p. 22). However, it is crucial to note that AI-assisted writing cannot entirely replace human-generated content. Human-generated writing effectively bridges prior knowledge with current understanding of a given topic, thereby conveying personal sentiments and logical perspectives (Hartwell & Aull, 2023). It is imperative for writers to judiciously employ AI applications when enhancing their compositions.

2.4. Research rationale and gaps

Prior investigations consistently demonstrated the influence of critical thinking skills (Dong & Chang, 2023; Spector & Ma, 2019; Yin et al., 2023), or the impact of self-directed learning capability on writing performance (Choy & Cheung, 2022; Lai et al., 2022a, 2022b; Tu, 2021; Waer, 2021). These studies underscored the substantial impact of critical thinking skills and self-directed learning on strengthening learners' writing proficiency when utilizing AI applications as aids. AI applications not only affect various stages of the writing process, including organization, language proficiency, and draft generation, but also significantly impact the quality of the final written work by providing automated feedback. Moreover, AI influences learners' writing motivation, thereby encouraging the utilization of critical thinking skills and self-directed learning competency in writing contexts.

Despite the growing interest in AI-assisted writing, these studies predominantly utilized a cross-sectional design, and there remains a paucity of research investigating the correlation between them, particularly in the context of combining critical thinking skills and self-directed learning competency. Therefore, the present study sought to explore the temporal correlation between critical thinking skills, self-directed learning competency, and AI writing across three times using a cross-lagged model in longitudinal study. Additionally, the hypotheses were developed as i) a reciprocal relationship exists between critical thinking skills and self-directed learning over three times; (ii) there are unidirectional relationships between critical thinking skills, self-directed learning competency, and AI-assisted writing across three times; (iii) Self-directed learning competency moderates the association between critical thinking skills and AI-assisted writing, as depicted in Fig. 2.

Based on these hypotheses, the research questions have been delineated as follows:

1. Are there the temporal relationships between critical thinking skills and self-directed learning and AI writing over three times?
2. Does self-directed learning competency moderate the critical thinking skills and AI writing?

3. Method

3.1. Participants

A sum of 204 sophomore EFL learners were randomly selected from various majors at a Chinese university. Among them, 109 were male, and 95 were female, with ages ranging from 19 to 21. All participants had perused the study of English as a foreign language for over 10 years and successfully passed the CET-4 examination during their first year, indicating proficiency at or above the intermediate level in English. These students had previously completed English writing classes in both their first and second semesters, during which they were introduced to AI applications such as *Quillbot*. As a result, they acquired basic writing strategies, including syntax, lexicon, and rhetoric, by harnessing AI applications to optimize their essay structures. It is pertinent to underscore that the students did not undergo any specific training in critical thinking or self-directed learning competency during their writing classes. As such, their

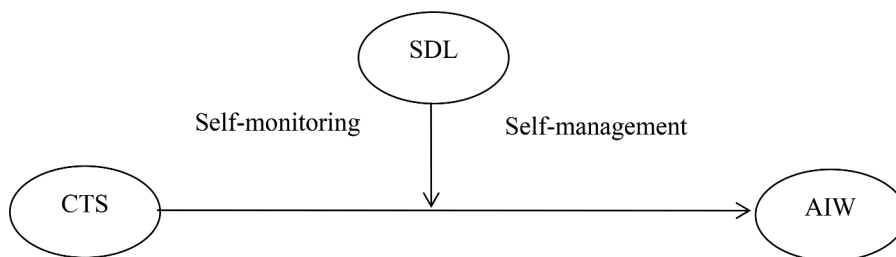


Fig. 1. Theoretical framework.

Note. CTS = critical thinking skills; SDL = self-directed learning; AIW = AI-assisted writing.

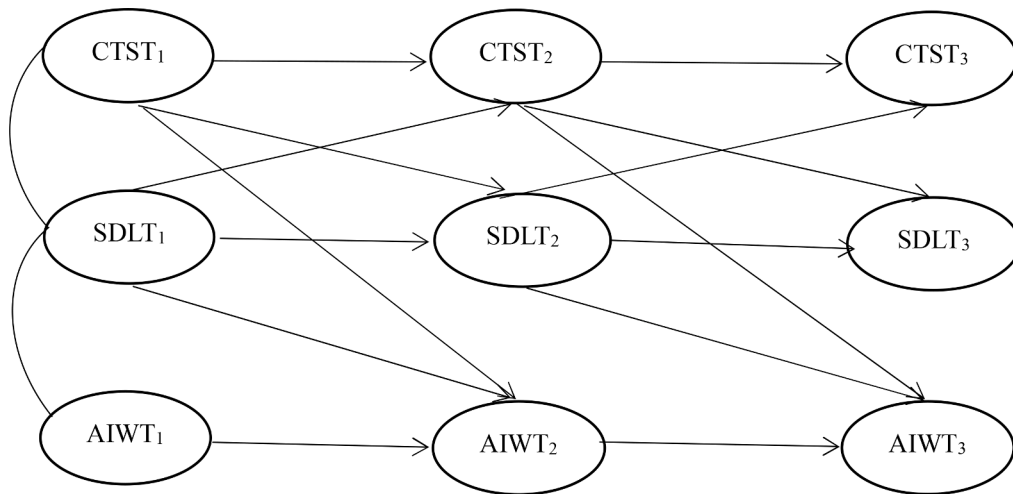
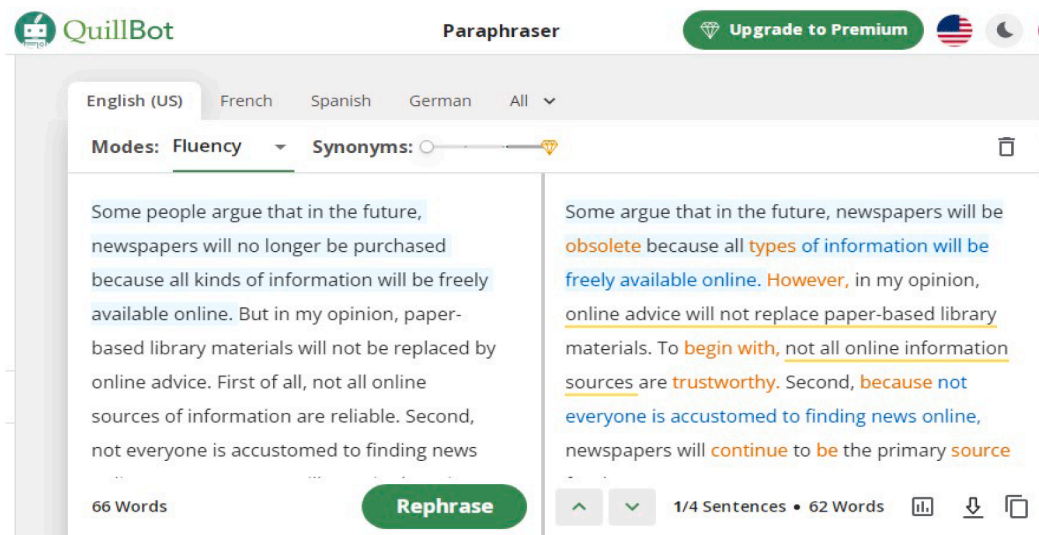


Fig. 2. The cross-lagged model between critical thinking skills, self-directed learning and AI writing.
 Note. CTS = critical thinking skills; SDL = self-directed learning; AIW = AI-assisted writing.



Original: Some people argue that in the future, newspapers will **no longer be purchased** because **all kinds of information** will be freely available online. **But** in my opinion, **paper-based library materials will not be replaced by online advice**. **First of all**, not all online sources of information are **reliable**. Second, not everyone is accustomed to finding news online, so newspapers will **remain the primary reference** for them.

Revision: Some argue that in the future, newspapers will be **obsolete** because **all types of information** will be freely available online. **However**, in my opinion, **online advice will not replace paper-based library materials**. **To begin with**, not all online information sources are **trustworthy**. Second, **because not everyone is accustomed to finding news online**, newspapers will **continue to be the primary source** for them.

Fig. 3. Writing revision on Quillbot.

current writing proficiency is based on their prior experience and exposure to AI writing tools, without direct focus on developing critical thinking and self-directed learning skills.

3.2. Instruments

The *California Critical Thinking Test* (CCTST), developed by Facione (1990), serves as an assessment tool to gauge learners' proficiency in employing critical thinking skills. It comprises 34 items, which are further categorized into different sub-skills: Interpretation and analysis, evaluation, and induction and deduction. The analysis dimension examines learners' capacity to present arguments and analyze information from diverse perspectives. Interpretation assesses learners' aptitude in articulating themselves clearly after processing and summarizing information. Evaluation evaluates learners' ability to assess information following elaboration. Induction and deduction gauge learners' competence in synthesizing information. For scoring, participants were awarded 1 point for providing correct answer and 0 point for incorrect answer. Extensive validity has been demonstrated in previous studies, establishing the CCTST as a highly valid instrument. The internal consistency of this questionnaire was evaluated through Cronbach's alpha coefficient, yielding a value of 0.933, thereby signifying a satisfied level of internal reliability.

The *English Self-directed Learning Competency Questionnaire* used in this study was originally developed by Xu et al. (2004) with the specific purpose of evaluating learners' aptitude for undertaking self-directed learning within the context of English language acquisition. The questionnaire comprises five dimensions, each encompassing a specific number of items: understanding purpose and setting goals, employing strategies, supervising the learning process and appraising learning outcomes, resulting in a total of 32 items. Participants were instructed to express their degree of concurrence or discordance on a Likert scale spanning from 1 ('strongly disagree') to 5 ('strongly agree'), reflecting their self-perceived proficiency in utilizing these self-directed learning strategies. The Cronbach's alpha coefficient calculated for this study yielded a value of 0.931, indicating strong internal consistency and reliability of the questionnaire.

3.3. Writing task

Traditional writing tasks typically require writers to independently organize their thoughts on a given topic, with criteria predominantly focusing on language proficiency such as topic relevance, coherence, cohesion, word choice accuracy, and grammar. However, many struggling writers often grapple with language proficiency issues, which may impede their ability to express their perspectives fluently. AI-assisted writing aids writers in improving their language proficiency for writing purposes, refining vocabulary selection and sentence structure. Also, it enables learners to effectively articulate their viewpoints and produce immediate self-feedback, assisting them in identifying and rectifying writing issues prior to draft submission. Through addressing language proficiency challenges, writers would proficiently convey their perspectives and autonomously engaged in writing activity. Thus, in this study, the writing task involved argumentative writing from Section 2 of the IELTS test, which was then revised and modified using the AI application *Quillbot*. This assessment was crafted to evaluate learners' proficiency in writing, aided by AI tools. Each participant was required to complete a 200-word essay based on a given topic. Additionally, participants were asked to present both their initial draft and the modified section after using *Quillbot* (refer to Fig. 3) to demonstrate how they utilized the AI tool to revise their writing. To evaluate the participants' writing, ten experienced lecturers, who had previously undergone IELTS writing standards training, assessed AI-assisted essay in conjunction with comparing original draft across several dimensions: topic relevance, cohesion and coherence, lexical choice and grammatical accuracy. Each dimension was scored on a scale from 0 to 5, and the ultimate score was derived from the average of these dimensions. The reliability of the AI writing task was evaluated, resulting in a high internal consistency.

3.4. Data procedures

The research was conducted in three stages. Initially, all participants engaged in offline learning in May 2022. In the second stage, all participants were required to transition to online learning in November 2022. Finally, in the third stage, the participants resumed offline learning in June 2023.

To begin the research process, permission was obtained from the university, and all participants who willingly participated in the study were included. Two assistants and four evaluated lecturers underwent one week of training to familiarize themselves with the research requirements and instructions. Subsequently, all voluntary participants were informed about the research instructions and ethical requirements. Participants were assured of the confidentiality of their information and were informed of their prerogative to withdraw from the research at anytime. Following the preparatory steps, the participants completed the *California Critical Thinking Skills Test* (CCTST), the *self-directed learning scale*, and the AI writing task, with the assistance of two trained assistants. After completing all tasks, all participants received a set of notebooks as a token of appreciation for their involvement in the study.

3.5. Data collection and analysis

After addressing the missing data, all the collected data was subjected to statistical analysis using SPSS 26.0 and AMOS 24.0. Descriptive analysis including means, standard deviations, and Bivariate Correlations were performed to analyze the associations between critical thinking skills, self-directed learning competence, and AI-assisted writing.

Subsequently, three cross-lagged models were constructed and examined using AMOS 24.0 to explore the temporal relationships between these variables. To assess the model fit, the recommended fit indices by Hair et al. (2010) were considered, including

Chi-Square (X^2) < 5.0, Goodness-of-Fit Index (GFI) > 0.90, Comparative Fit Index (CFI) > 0.90, Tucker-Lewis Index (TLI) > 0.90, and Root Mean Square Error of Approximation (RMSEA) < 0.08. The X^2 statistic evaluated the overall fit of the causal path diagram to the observed data, while the GFI, CFI, and TLI was utilized to gauge the degree of fit between the model and the empirical data. The RMSEA provided insights into the pattern of residuals, serving as a critical indicator of fit. To assess convergent validity, all factor loadings were examined to be greater than 0.05 but less than 1.0, and the average variance extracted (AVE) was ensured to exceed 0.50. Reliability was evaluated using the Constructed Reliability (CR), where a value above 0.70 indicated satisfactory reliability (Kline, 2011). Furthermore, in Amos 24.0, during the multi-group analysis, a moderate effect was identified when the Beta value for one of the groups was significant ($p < 0.05$), and the t -value (critical ratio) exceeded 1.96 (Hair et al., 2010).

4. Results

Table 1 displayed the descriptive statistics, encompassing the Mean, Standard Deviations, and correlation coefficients, depicting the interrelationships between critical thinking skills, self-directed learning competency, and AI-assisted writing across the three measurement points. As evidenced in the table, significant positive associations emerged between critical thinking skills and self-directed learning competency (r ranged from 0.316 to 0.503), between critical thinking skills and AI-assisted writing (r ranged from 0.185 to 0.345), and between self-directed learning competency and AI-assisted writing (r ranged from 0.205 to 0.337).

4.1. Temporal correlation between critical thinking skills and self-directed learning competency

The temporal interplay between critical thinking skills and self-directed learning competency was examined through a cross-lagged model, depicted in Fig. 3. The path coefficients within the model demonstrated statistical significance, and the model fit indices attested to a favorable fit, with $X^2 = 1.590$, GFI = 0.903, CFI = 0.959, TLI = 0.950, and RMSEA = 0.054. As depicted in Fig. 4, the temporal interrelationship between critical thinking skills and self-directed learning competency appeared to be reciprocal. More specifically, critical thinking skills (T_1) positively predicted self-directed learning competency (T_2) ($\beta = 0.30, p < .01$). Similarly, self-directed learning competency (T_1) and (T_2) positively predicted critical thinking skills (T_2) ($\beta = 0.24, p < .01$) and (T_3) ($\beta = 0.28, p < .05$), irrespective of the different learning modes. However, critical thinking skills (T_2) did not predict self-directed learning competency (T_3).

4.2. Temporal correlation between critical thinking and AI-assisted writing

Fig. 5 presented the temporal interplay between critical thinking and AI-assisted writing through a three-wave cross-lagged model. The path coefficients were found to be statistically significant, and the model fit indices affirmed an alignment of the model with $X^2 = 1.518$, GFI = 0.908, CFI = 0.957, TLI = 0.947, and RMSEA = 0.051, signifying an acceptable level of fit for the model. Furthermore, the analysis revealed that critical thinking skills (T_1) positively predicted AI-assisted writing (T_2) ($\beta = 0.23, p < .01$). Similarly, critical thinking skills (T_2) also positively predicted AI-assisted writing (T_3) ($\beta = 0.29, p < .01$). These findings suggested that higher levels of critical thinking skills were associated with improved performance in AI-assisted writing tasks over time.

4.3. Temporal correlation between self-directed learning and AI-assisted writing

As depicted in Fig. 6, the temporal correlation between self-directed learning competency and AI-assisted writing exhibited a noteworthy positive significance. The path coefficient demonstrated statistical significance, and the model fit indices attested to a favorable alignment of the model with $X^2 = 1.609$, GFI = 0.904, CFI = 0.948, TLI = 0.949, and RMSEA = 0.055. Moreover, the analysis revealed that self-directed learning competency (T_1) positively predicted AI-assisted writing (T_2) ($\beta = 0.20, p < .05$). Similarly, self-directed learning competency (T_2) also positively predicted AI-assisted writing (T_3) ($\beta = 0.21, p < .05$) regardless of whether the learning was conducted in an online or offline mode. These findings suggested a positive association between learners' self-directed

Table 1
Descriptive analysis and Correlations between research variables at three times.

	1	2	3	4	5	6	7	8	9
1.CTST ₁	1								
2.CTST ₂	0.402	1							
3.CTST ₃	0.431	0.433	1						
4.SDLT ₁	0.362	0.316	0.383	1					
5.SDLT ₂	0.348	0.458	0.366	0.405	1				
6.SDLT ₃	0.421	0.355	0.368	0.425	0.503	1			
7.AIWT ₁	0.266	0.239	0.185	0.337	0.234	0.263	1		
8.AIWT ₂	0.251	0.278	0.223	0.275	0.229	0.241	0.333	1	
9.AIWT ₃	0.327	0.345	0.240	0.205	0.272	0.280	0.321	0.449	1
M	3.21	3.42	3.22	3.00	3.27	3.12	3.22	3.65	3.07
SD	1.054	1.023	1.058	1.092	1.036	1.131	0.983	0.798	0.773

Note ** Correlation is significant at the 0.01 level (2-tailed) * Correlation is significant at the 0.05 level (2-tailed).

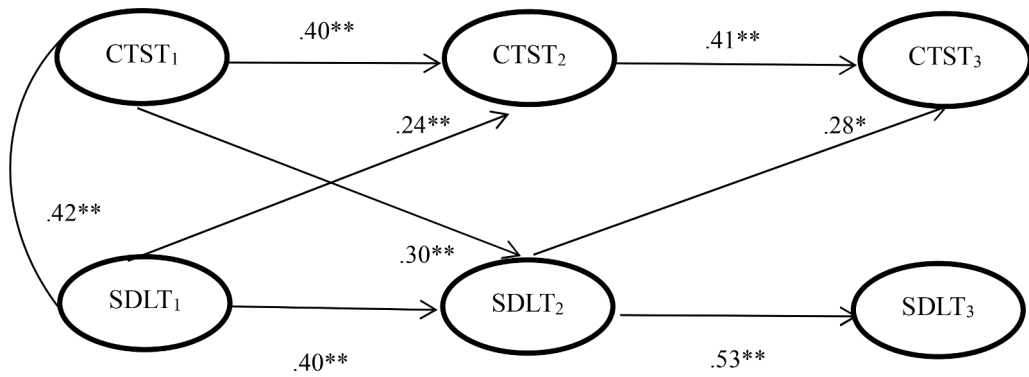


Fig. 4. The cross-lagged model of critical thinking skills and self-directed learning.

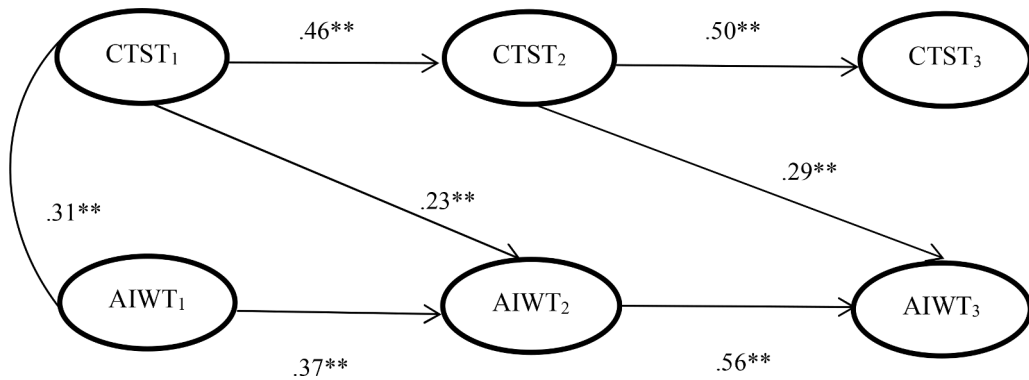


Fig. 5. The cross-lagged model of critical thinking skills and AI writing.

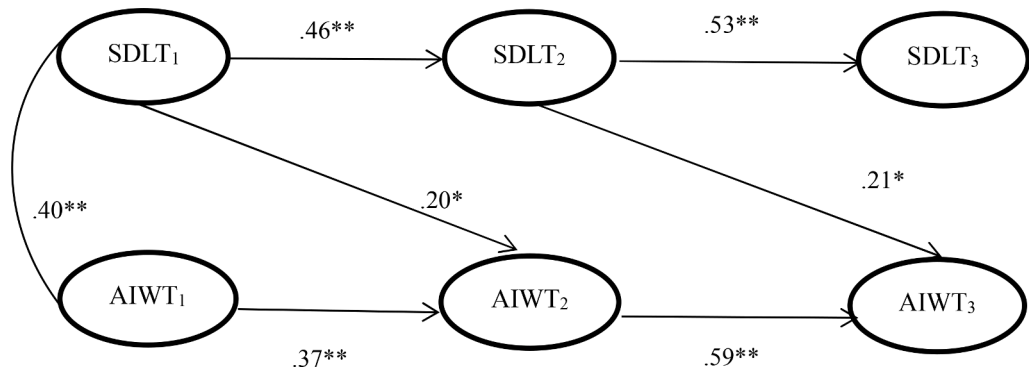


Fig. 6. The cross-lagged model of self-directed learning and AI writing.

learning competency and improved performance in AI-driven writing tasks, regardless of the learning mode.

4.4. Self-directed learning competency as a moderator on critical thinking skills and AI-assisted writing

The moderating influence of self-directed learning competency was elucidated through Fig. 7 and Table 2. The model fit ($X^2 = 1.134$, GFI = 0.958, CFI = 0.990, TLI = 0.990, RMSEA = 0.026) was assessed using various fit indices, which demonstrated a satisfactory fit.

As shown in Table 4, the results indicated that self-directed learning competency (T_2) moderated the correlation between critical thinking skills (T_1) and AI writing (T_2) in online learning mode. Specifically, when the self-directed learning competency is at a low level (LL $\beta = 0.312$, $p = 0.002 < 0.05$), the impact of critical thinking skills on AI-assisted writing did not exhibit statistical significance. However, when the self-directed learning competency was at a high level (HL $\beta = -0.203$, $p = 0.292 > 0.05$, $t = -2.852 > |1.96|$), a

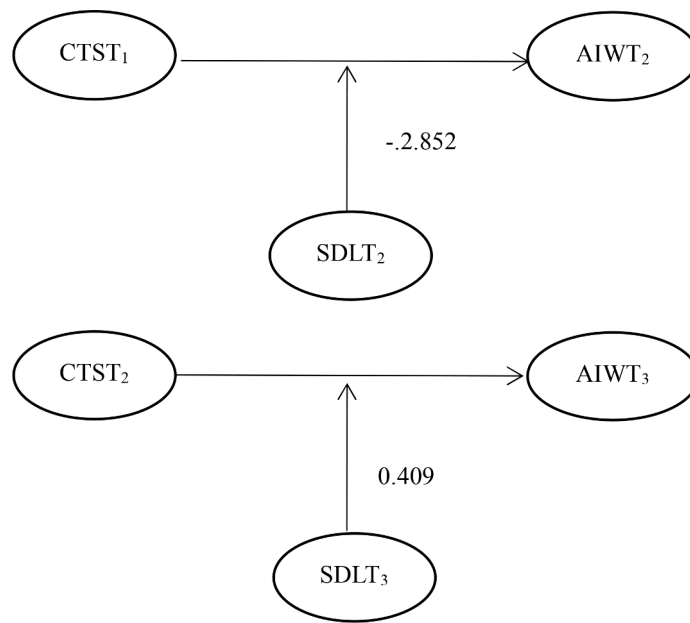


Fig. 7. Two longitudinal moderation models.

Table 2
Moderate analysis.

Moderation model	Multi-group	Beta	CR	P	t	Decision
CTST1*SDLT2→ AIWT2	Low level	0.312	3.086	0.002	-2.852	Moderation
	High level	-0.203	-1.054	0.292		
	Low level	0.367	3.005	0.003		
CTST2*SDLT3→ AIWT3	High level	0.394	2.022	0.043	0.409	No moderation

notable correlation was observed between critical thinking skills and AI-assisted writing. This suggested that self-directed learning competency influences the utilization of critical thinking skills on AI-assisted writing in online learning. Conversely, in offline learning mode, self-directed learning competency (T₃) did not moderate the correlation between critical thinking skills (T₂) and AI-assisted writing (T₃) (LL β = 0.367, p = 0.003; HL β = 0.394, p = 0.043; t = 0.409 < |1.96|). This finding suggested that the moderating influence of self-directed learning competence on the impact of critical thinking skills on AI-assisted writing did not manifest in the offline learning mode.

5. Discussion

This study substantiated the significant relationships between critical thinking skills, self-directed learning competency, and AI-assisted writing across longitudinal study. These findings have contributed to the development of Garrison’s (1997) theory, which involve integrating critical thinking skills into self-directed learning. This expansion of the role of self-directed learning in writing within AI-assisted technology entails leveraging critical thinking skills to analyze the performance of EFL learners in AI-assisted writing. To explore these relationships further, a three-wave cross-lagged model was employed, allowing for the examination of temporal associations between critical thinking skills, self-directed learning competency, and AI-assisted writing over three times in diverse learning modes.

Firstly, the findings unveiled a temporal interplay between critical thinking skills and self-directed learning competency from Time 1 to Time 2. This discrepancy between the two learning modes aligned with prior studies undertaken by Jin and Ji (2021); Khalid et al. (2020), and Song et al. (2022) which also found that learners possessing a heightened level of self-directed learning competence tend to exhibit greater proactivity in assuming their learning responsibilities. They also displayed greater independence and reduced reliance on external assistance, particularly in online learning (Song et al., 2022). As a result, learners’ motivation is heightened, and they actively enhance their critical thinking abilities.

However, it is worth nothing that while self-directed learning positively predicted critical thinking skills, critical thinking skills did not significantly predict self-directed learning between Time 2 and Time 3. This result diverged from a study that underscored the role

of critical thinking skills in fostering learners' self-directed learning as they begin to critically filter learning materials, summarize and analyze them argumentatively, and infer the learning outcomes reasonably (Jin & Ji, 2021). The findings suggested that self-directed learning can play a substantial role in fostering the development of critical thinking skills, particularly in online learning settings where learners are encouraged to adopt a proactive and independent approach to their learning process. Conversely, in offline learning, the role of critical thinking skills in predicting learning competency such as writing proficiency may not be as pronounced maybe due to the absence of critical thinking guidance and training (Yin et al., 2023).

Secondly, this study has revealed a unidirectional temporal correlation between critical thinking skills and AI-assisted writing across three times. Specifically, critical thinking skills predict AI-assisted writing in different learning modes, marking a consistent with prior research (Bağ & Gürsoy, 2021; Ebadi & Rahimi, 2018; Yin et al., 2023). These studies predominantly centered on the direct impact of critical thinking skills on writing, emphasizing how these skills enable learners to comprehend topics effectively, construct clear and coherent thesis statements, organize their discourse logically, and articulate ideas through thoughtful analysis and coherent explanations. Furthermore, given that some students struggle with over-reliance on AI tools and face challenges related to language proficiency, it is essential to focus on the critical use of AI tools in writing activities. For example, the study by Ebadi and Rahimi (2018) revealed that *WebQuests*, an online inquiry-oriented tool, had a notable impact on enhancing learners' abilities in understanding, planning, and evaluating. However, it did not significantly affect inductive and inference skills in writing, possibly because learners predominantly relied on *WebQuests* as their primary source for gathering information. As stated by Bağ and Gürsoy (2021), critical thinking proves to be an effective instrument for heightening learners' awareness, enabling them to achieve language skill goals by making their thinking processes visible and purposeful in English courses.

In contrast, the result of reverse relationship between AI-assisted writing to critical thinking skills was not observed, possibly due to the inaccuracy of AI tools' responses, leading to anxiety and confusion among learners in their utilization of these assisted tools (Kohnke et al., 2023). Another explanation is that learners tend to prioritize using AI-assisted tools for vocabulary enhancement and identifying grammar errors in their essays (Hartwell & Aull, 2023; Marzuki et al., 2023). Hence, the current study's findings contributed to the literature by employing AI application on improving language proficiency when learners skillfully analyze and process information, thoughtfully interpret their own ideas, and critically evaluate their writing output, however, effectively utilization of AI-assisted tools should be attention. Comparing these results with prior findings may not yield direct parallels due to the novel exploration of the interplay of critical thinking skills and AI-assisted writing in this study.

Thirdly, the results unveiled a unidirectional temporal connection between self-directed learning competence and AI-enhanced writing, with no evidence of a reverse relationship. According to previous research (Choy & Cheung, 2022; Khalid et al., 2020; Tu, 2021) has shown learners with self-directed learning competency are more inclined to engage in self-monitoring of their strengths and weaknesses, acquiring knowledge and taking proactive steps to revise their writing plans through self-evaluation. Such effective regulation during the compositional process contributes to mitigating writing anxiety. In Khalid et al.'s (2020) study, the adoption of self-directed learning strategies emerged as a catalyst, empowering learners to actively oversee their learning process and achieve superior learning outcomes when compared to conventional learning modes reliant on teacher or peer feedback. Correspondingly, engaging in self-directed learning with the aid of online writing assistant tools enable learners to generate a greater number of ideas for setting writing goals and effectively structure their compositions (Choy & Cheung, 2022). This approach facilitate the efficient receipt of writing feedback, thereby motivating learners to participate in collaborative activities (Hartwell & Aull, 2023). Also, they highlighted that learners lack familiarity with these technological aids due to limited exposure. Tu (2021) and Lai et al. (2022a) further underscored the impact of weak technological competency, asserting that it hampers learners in developing self-directed learning competency to reach their writing goals.

Conversely, it is surprising that reverse relationship was not discovered, possibly due to the overreliance on AI-assisted tools without independently generating their own perspectives. This underscored the importance of considering the ethical implications (Cotton et al., 2023) associated with AI-assisted tools in writing generation. Hence, the findings in this study underscored the pivotal role of self-directed learning in influencing AI-assisted writing, it also suggested that learners are capable of independently managing their learning process with online writing assistant tools with greater confidence and reduced apprehension in both online and offline learning modes.

Finally, the findings of this study further unveiled self-directed learning competency moderated the association between critical thinking skills and AI-assisted writing from Time 1 to Time 2. This aligned with the theories proposed by Garrison (1997) and Morris (2019) indicating that self-directed learning assists learners in critically establishing learning goals, taking control of the learning process, and constructing meaningful compositions. As stated by Lai et al. (2022b), the self-directed learning process is intricately associated with cognitive, metacognitive, and affective factors. These encompass a spectrum of strategies, spanning from fundamental cognitive processes like comprehension to higher cognitive functions such as monitoring and assessing their learning assignments with the objective of effectively regulating their learning processes.

Therefore, we argued that self-directed learning cultivates learners' competence in establishing purposeful goals, judiciously selecting suitable learning strategies, and evaluating learning outcomes. This, in turn, may enhance their proficiency in analyzing, interpreting, and synthesizing learning materials, empowering them to critically adapt and refine their writing processes. Although research mentioned the function of self-directed learning competency in writing (Teng, Wang, & Zhang, 2022, Teng & Zhang, 2024), these existing literature lacked sufficient exploration of the moderating effect of self-directed learning on the interplay between critical thinking skills and AI-assisted writing, thereby leaving a gap in the understanding of this aspect.

Nevertheless, self-directed learning did not moderate in Time 2 and Time 3. This can be attributed to the fact that, while some students are proficient in using AI-assisted tools to revise their writing (Khodaei et al., 2022), others do not perceive the value of these tools in an online writing context (Lai et al., 2022a). Furthermore, there is a lack of self-directed learning in effectively using AI-assisted

tools, particularly when students are engaged in writing tasks (Hartwell & Aull, 2023). Future studies could consider various individual affective factors, such as self-efficacy, in AI-assisted writing performance to explore the impact of self-directed learning through the utilization of critical thinking skills in writing activities.

6. Conclusion

This study elucidated significant associations between critical thinking skills, self-directed learning competency, and AI-assisted writing over the course of three assessments. To examine these temporal correlations, a three-wave cross-lagged model was employed. Although the temporal associations between critical thinking skills and self-directed learning exhibited a bidirectional pattern across three times, the connections between critical thinking skills, self-directed learning, and AI-assisted writing were unidirectional. Of particular importance, the findings indicated that self-directed learning indeed exerted a moderating influence on the relationship between critical thinking skills and AI-enhanced writing, but this effect was observed exclusively from Time 1 to Time 2. Conversely, from Time 2 to Time 3, self-directed learning did not exhibit a moderating effect on the interplay of critical thinking skills and AI-assisted writing.

This study holds significant implications for educators and teachers, offering valuable insights into effective writing instruction. With the advancement of AI-assisted tools in the writing classroom, it is essential for teachers to guide learners in using these tools judiciously for revising writing through feedback. Moreover, teachers should prioritize cultivating students' self-directed learning competency in using AI-assisted tools for writing. This entails guiding them to independently organize and monitor their writing process, critically utilize AI applications to analyze information, make sound judgments, and strategically integrate these tools for writing.

As future studies unfold, it is recommended to incorporate English self-directed learning competency, critical thinking skills, and AI-assisted applications as essential variables. This approach will deepen our understanding of writing-related research and its implications for language learners. Such comprehensive investigations will undoubtedly contribute to advancing effective pedagogical practices and empowering learners in the field of writing.

These findings provide valuable insights into the intricate interplay among critical thinking skills, self-directed learning, and AI-assisted writing across diverse learning modes. However, future investigations could incorporate writing text analysis utilizing AI applications to strengthen the evidence concerning the influence of these learning skills on writing. Additionally, for a more comprehensive understanding, future research could extend its scope to encompass ESL learners, thus encompassing a broader population and facilitating cross-comparisons between language learners.

Statement on data and ethics

The research data can be obtained from the authors upon request. The research received university ethical approval.

CRedit authorship contribution statement

Xiaolei Shen: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Mark Feng Teng:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – review & editing.

Declaration of competing interest

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Xiaolei Shen is a PhD candidate in TESL at the University Putra Malaysia at the Faculty of Educational Studies. She is fascinated about learning strategies such as metacognitive strategies and critical thinking skills.

Mark Feng Teng, Ph.D., is Associate Professor at Macao Polytechnic University. He was the recipient of the 2017 Best Paper Award from the Hong Kong Association for Applied Linguistics (HAAL), 2023 Best Paper Award in social sciences from Education Ministry of China. His research portfolio mainly focuses on L2 vocabulary acquisition, and L2 writing from the perspective of metacognition. His publications have appeared in international journals, including *Applied Linguistics*, *TESOL Quarterly*, *Language Teaching Research*, *System*, *Applied Linguistics Review*, *Computer Assisted Language Learning*, *Computers & Education*, *Foreign Language Annals*, and *IRAL*, among others. His recent monographs were published by Routledge, Springer, and Bloomsbury. He also edited and co-edited special issues for international journals, including *Journal of Writing Research*, *Studies in Second Language Learning and Teaching*, and *TESOL Journal*.