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Exploring the Synergy of Artificial Intelligence and Augmented Reality in Developing EFL Students' Critical Thinking

[1]Malihe Aerabi
[2]Fatemeh Hemmati*
[3]Hassan Soleimani

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Abstract: A major concern in recent decades, with the emergence of technologies such as Artificial Intelligence (AI) and Augmented Reality (AR) in English language education, has been their impact on learners' critical thinking skills. This study aims to examine how artificial intelligence and augmented reality tools influence EFL students' critical thinking in writing, and explore their perceptions of how these technologies, when integrated into EFL writing tasks, might be effective. To this end, an explanatory mixed-methods design was used, and 33 EFL students were selected non-randomly and assigned randomly to experimental and control groups. The intervention integrated augmented reality-based exploration with artificial intelligence-driven idea generation, helping learners engage in prewriting, drafting, and revision. The materials included the Evolve 3 textbook, Perplexity AI, and Leo AR. The California Critical Thinking Skills Test (CCTST) was administered before and after the intervention. The Paul-Elder critical thinking rubric was utilized to evaluate post-writing tasks. Furthermore, a semi-structured interview was conducted with the experimental group. The results of ANCOVA indicated a significant positive impact of artificial intelligence and augmented reality tools on learners' critical thinking in writing skills. These findings could influence teachers, students, material developers, and the education system.

***Keywords*:** Artificial intelligence, Augmented reality, Critical thinking, EFL students' perception, Writing skills

Introduction

Education systems worldwide embrace new and integrated teaching and learning processes that utilize various forms of technology. Rideout et al. (2010) noted that with the rapid advancement of technology, the number of students utilizing digital devices has significantly increased. Technologies and digital developments that utilize the internet are integral features for students (Kennedy et al., 2008). Blake (2024) emphasized that Artificial Intelligence (AI) can adapt to various learning strategies and needs, providing personalized content and responses that support students. According to Wang and Panahi (2023), diverse AI tools, including QuillBot, WordTune, Writesonic, and ChatGPT, have been identified for their ability to assist EFL learners at various stages of the writing process, and these applications are evident throughout these steps. Dizon and Gold (2023) reported that using AI in writing not only increases learners' writing accomplishments but also alleviates writing-related anxiety and, in general, fosters motivation. Therefore, according to Wang (2024), AI tools can affect the writing process in a way that, if utilized appropriately, may enhance learners' ability to write in a second language.

[1] PhD Candidate in TEFL, Email: aerabi.pishtaz@yahoo.com; Department of TEFL, Payame Noor University, Tehran, Iran.

[2] Associate Professor of TEFL (Corresponding Author), Email: hemmati@pnu.ac.ir; Department of TEFL, Payame Noor University, Tehran, Iran.

[3] Associate Professor of Applied Linguistics, Email: h_soleimanis@pnu.ac.ir; Department of TEFL, Payame Noor University, Tehran, Iran.

Virata and Castro (2019) believe that technology creates innovative and inventive methods within education and could be an impressive medium for encouraging students' learning. The Augmented Reality (AR) applications used in teaching and learning display many aims, uses, and experiments that students cannot obtain from first-hand experience in various aspects because of their impracticability in the real world, and they are techniques that might be used in many science fields that are unreachable, unattainable, and impossible to travel to (Pellas et al., 2019). Dunleavy et al. (2009) believe that the employment of AR applications as part of teaching a topic has the properties of being constructivist, problem-solving-oriented, learner-centered, authentic, collaborative, creative, personalized, meaningful, challenging, participative, interactive, entertaining, cognitively enriching, contextual, and encouraging learning experiences. From the perspective of EFL education, critical thinking has emerged as a crucial factor in fostering writing proficiency. Yin et al. (2023) emphasized that merging critical thinking with EFL writing instruction enhances learners' ability to make coherent arguments, analyze diverse views, and engage in reflective reasoning. Accordingly, Aerabi et al. (2026) highlighted that learners with high critical thinking are free to develop their learning capacities, resulting in significant personal interactions.

Despite the rapid use of technology-empowered tools in teaching and learning processes, there is a remarkable lack of integration of AI tools and AR technology into the learning process to discover their probable impacts on learners' critical thinking. An investigation of the literature review revealed that no study has focused on the synergistic effects of AI and AR tools and their effects on critical thinking in EFL writing. This study aims to fill this gap by exploring the probable impact of AI tools and AR technology on critical thinking in EFL writing and comparing it with the traditional instructions of writing in EFL classrooms. By doing so, this research not only concerns the fostering body of knowledge on integrating AI and AR tools into the learning process but also provides valuable information on the practical application of such tools in the language learning process, especially within the Iranian EFL context, thereby enriching both theoretical and practical discussions in the field.

Literature Review

This study proposes a conceptual framework that combines multimodal learning theory, constructivist learning theory, and critical thinking frameworks to investigate how AI and AR may foster EFL writing. Multimodal learning recommends that learners obtain knowledge more effectively when instruction involves multiple sensory modalities, such as visual, auditory, and kinesthetic (Fleming & Mills, 1992). According to Mayer's (2005) Cognitive Theory of Multimedia Learning, learning is fostered when learners actively combine information from both verbal and visual media. The combined use of AR and AI, according to this theory, might provide a dual-channel environment that supports active cognitive processing. On the basis of Vygotsky's constructivist theory (1978), learners make knowledge actively through interaction, problem solving, and social negotiation.

Critical Thinking in EFL Writing

Critical thinking in EFL writing concerns reasoning, argumentation, and the evaluation of evidence, not solely linguistic accuracy (Stapleton, 2001). Paul and Elder (2008) define critical thinking as the ability to analyze, evaluate, and improve thought. AI can help with this through prompting, questioning, and modeling critical discourse. AR can activate reflective responses by immersing learners in thought-provoking or controversial contexts. Recent advances in AI have sparked considerable interest in language education because of its potential to support higher-order thinking. Rather than functioning only as writing assistants, AI tools can facilitate brainstorming, generate multiple ideas, pose reflective questions, and provide feedback that encourages learners to evaluate and refine their ideas. In other words, the rapid use of generative AI in the teaching and learning processes is not extraordinary for research investigating the possible roles of AI for writing, such as Woo et al. (2023), who equipped learners with instruction in AI text with tools for inspired writing, who discovered that the learners were capable of choosing tools that made a variety of opinions and failed content that diverged from their existing perceptions, and García Botero et al. (2021), who reported that individuals who were provided

self-management practices showed a markedly higher level of activation in Duolingo than did the learners who did not, who were able to choose tools that produced higher test scores in French writing.

Liu and Wang (2024) reported that AI tools such as ChatGPT-3.5, Bodoudou, and SummarizBot can enhance learners' critical thinking skills during English literature classes. However, the educational value of AI remains contested. Although many studies have reported improvements in writing quality and learner engagement, others have cautioned that excessive dependence on AI-generated content may reduce learners' cognitive effort. For instance, Ju (2023), in an experimental study, indicated that complete reliance on AI tools for writing practices results in a significant reduction in learning efficacy. This study suggests that overreliance on AI can impair critical thinking and comprehension. Parallel to developments in AI, AR has emerged as an effective multimodal technology for creating authentic and interactive learning contexts. The findings of the study conducted by Wang (2017) illustrated that AR can effectively develop critical thinking in EFL writing through immersive and collaborative learning experiences. However, this study was conducted over a limited period, which raises a problem in evaluating long-term effects.

Taken together, previous research indicates that both generative AI and AR have the potential to enhance higher-order thinking in language learning, yet important gaps remain. Existing studies have typically examined these technologies independently, making it difficult to understand whether their complementary strengths can produce greater benefits when integrated. AI provides cognitive support through idea generation, questioning, and feedback, whereas AR offers contextualized and immersive experiences that stimulate observation and reflection. Despite these complementary affordances, empirical evidence examining their combined influence on critical thinking in EFL writing is lacking. Addressing this gap, the present study investigates whether integrating Leo AR and Perplexity AI within EFL writing instruction enhances learners' critical thinking and explores students' perceptions of this multimodal learning approach. For this purpose, the following research questions were formulated:

Research Question One: Do AR and AI tools integrated with EFL writing activities have any significant effect on learners' critical thinking?

Research Question Two: What are EFL students' perceptions of how AR and AI tools influence their critical thinking during writing activities?

Methodology

This explanatory mixed-methods study examined the critical thinking of EFL students before and after the integration of AI and AR tools while minimizing the influence of extraneous variables. Thirty-three female EFL students were purposively and conveniently selected from an institute in Qom, Iran, during the spring and summer semesters of 2025 for a two-month program. Each semester included 12 sessions, each lasting 90 minutes, held three times a week. The curriculum was based on an integrated, multi-skilled syllabus that prioritized writing skills. The participants aged 18-23 years (M = 19.55, SD = 3.83) had at least five years of English learning experience across various educational backgrounds and were divided into an experimental group (N = 16) and a control group (N = 17). Two weeks before the study, the Oxford Placement Test (Allen, 2004) was administered to confirm the homogeneity of the students' English proficiency levels. An independent-samples *t-test* revealed no significant differences between the groups (t (32) = 0.63, p = 0.53, Cohen's d = 0.22), which were classified as pre-intermediate based on the Common European Framework of Reference for Language (CEFR B1). One week before the intervention, the experimental group was introduced to the Leo AR Camera app and Perplexity AI, along with their functionalities, through a six-hour training course spread over three days.

Materials and Instruments

Evolve 3

Evolve 3 is an intermediate-level EFL textbook written by Hendra et al. (2019) and published by Cambridge University Press, designed to promote language skills through communicative and integrated tasks.

Perplexity AI

Perplexity AI, Inc. is a privately held company that was established in 2022 and is based in San Francisco, California. It was cofounded by Aravind Srinivas, Denis Yarats, Johnny HO, and Andy Konwinski. The official website of Perplexity AI is https://perplexity.ai. Perplexity AI was chosen because it functions as a conversational search and brainstorming tool that creates multiple perspectives, vocabulary suggestions, and guiding questions supported by referenced information, thereby motivating learners to compare, evaluate, and refine ideas rather than simply generating complete essays. This feature aligns with the study's emphasis on critical thinking during the prewriting stage.

Leo Augmented Reality

Leo AR was founded in 2017 by Dana Loberg and Sahin Boydas in San Francisco. Leo AR is a mobile application that enables users to create and visualize virtual content within real-world contexts. Leo AR was selected because it enables learners to create and interact with three-dimensional AR scenes using mobile devices without requiring specialized equipment. Leo AR required less training compared with more technically demanding AR platforms, making it suitable for classroom implementation with intermediate EFL learners.

Oxford Placement Test (OPT)

The Oxford Placement Test (Allen, 2004) was employed to determine the differences in learners' language levels. It consists of 60 questions on a scale from 0 to 120 to examine their language proficiency. This test included two sections: grammatical and pragmatic knowledge, along with students' ability to apply this knowledge when communicating a range of meanings while listening, and explaining the learners' language proficiency level from the beginner level (A1) to the very advanced level (C2), with 20 points relating to each CEFR level.

California Critical Thinking Skills Test (CCTST)

The second instrument employed in this research was the CCTST, which challenges the participants' reasoning skills. In the present research, the Persian version of the CCTST was conducted in a timed format (50 minutes). Form A, indicating the pre-test, and Form B, administered as the post-test, were answered by the participants. The total score for the California Critical Thinking Test was 34. These 34 items evaluate five categories of critical thinking ability, which encompass analysis (9 items), evaluation (14 items), inference (11 items), deductive reasoning (16 items), and inductive reasoning (14 items). In addition to an overall critical thinking score, the CCTST reports scores for each cognitive skill domain. Because the instrument is based on an integrated model of critical thinking, several test items contribute to more than one cognitive skill score. The CCTST is a multiple-choice test designed to be scored dichotomously, featuring one correct answer and three or four distractors. The test's reliability has been reported to range from 0.78 to 0.80 on the basis of Cronbach's alpha (Facione, 1990). The Persian version was employed to ensure that the participants fully understood critical thinking (Khalili & Hosseinzadeh, 2003). On the other hand, the internal consistency of the questionnaire was assessed via Cronbach's alpha, which was found to be $\alpha = 0.83$, indicating acceptable reliability.

Paul-Elder Critical Thinking Rubric

The three-dimensional critical thinking model provided by Paul and Elder (2013) encompasses aspects of thought reasoning, intellectual standards, and intellectual traits. A special writing rubric according to

the Paul–Elder Critical Thinking Model was employed to evaluate participants' post-written tasks. This rubric contains nine factors of thought (Paul & Elder, 2001) and was improved by selected intellectual standards (clarity, accuracy, precision, relevance, logic, depth, significance, fairness, and breadth) to make a detailed assessment of the quality of critical thinking presented in student writing. Each factor was scored on a 3-point scale, with intellectual standards used to facilitate scoring. Two trained raters evaluated all the writing tasks, and inter-rater reliability was established.

Interview

For the qualitative phase, a semi-structured interview was adapted from Ibáñez and Delgado-Kloos (2018), Holmes et al. (2019), Facione (2011), Facione (1990), and Paul and Elder (2008). The interview protocol consisted of five open-ended questions and was administered to a purposive sample of learners from the experimental group after the completion of the intervention. The interview aimed to gain an in-depth understanding of students' experiences, perceptions, and challenges regarding the use of these technologies in EFL writing. The interview protocol consisted of open-ended questions focusing on learners' experiences with the intervention. For instance, 1) How do you think using AR tools (like Leo AR) helped you generate or organize ideas for your writing? 2) Did interacting with AI tools (such as Perplexity AI) during writing make you reflect more deeply on your arguments or decisions? Can you give an example? 3) Were there moments when using AR or AI made you question your assumptions or revise your writing more critically? 4) Did you find AR or AI tools more helpful for developing the content of your writing or for organizing it logically? Why? 5) After using AR and AI in writing tasks, do you feel more confident in evaluating and improving your writing critically? Why or why not? Each interview lasted 20-30 minutes, and all the audio recordings were transcribed for coding and thematic analysis. The transcripts were shared with the participants to verify the accuracy of the data. To ensure the content validity of the interviews, the questions were evaluated by three experts in EFL pedagogy to check the questions' clarity and relevance. Reliability was estimated through inter-coder agreement, as 20% of the responses were double-coded by an independent rater. Inter-coder agreement was obtained via Cohen's Kappa, resulting in a value of 0.85.

Procedure

The study followed quantitative and qualitative phases as follows:

Quantitative Phase

Initially, the participants completed the OPT to confirm homogeneity in proficiency. The CCTSI was subsequently administered to both groups as a pre-test. The participants were familiarized with the topics and expectations of the writing tasks aligned with Units 10–12 of the textbook. The English classes were conducted over 24 sessions, each lasting 90 minutes, with the same teacher, who had 13 years of experience teaching English, leading both the experimental and control groups. The classes for the experimental group took place on even days, whereas those for the control group occurred on odd days.

Experimental Group

The students in the experimental group received instruction with the support of AR and AI technologies in all three writing tasks. The treatment integrated AR and generative AI within the framework of the Evolve textbook writing activities. This multimodal procedure provided both visual and cognitive scaffolds to enhance idea generation, critical thinking, and improved writing activity. The AR and AI activities were designed to support the pre-writing, drafting, and revising stages of the writing process while promoting critical thinking. The writing topics were selected from the Evolve textbook, and each task followed the same instructional sequence. First, learners used the Leo AR application to create an augmented scene by placing three-dimensional virtual objects into their real environment using their

smartphones. The objects were selected to match the topic of the writing lesson. For example, in a narrative writing lesson, learners created a scene containing a park, a lost backpack, and a dog. They observed the scene and answered teacher-designed guiding questions such as: What is happening? Who might be involved? What could happen next? and Why do you think so? These questions encouraged learners to analyze the scene, infer relationships, and generate possible storylines. Next, learners used Perplexity.ai during the pre-writing stage. They entered prompts based on their AR scenes (e.g., Suggest three possible storylines for a lost backpack in a park or Generate vocabulary for describing a surprising event). Rather than copying the AI-generated responses, learners evaluated the suggested ideas, compared alternatives, selected the most appropriate information, and modified it according to their own writing purposes. This evaluation process was intended to promote critical thinking through analysis, judgment, and decision-making. Finally, learners completed the writing task from the Evolve textbook by integrating ideas developed through both AR exploration and AI-assisted brainstorming. During revision, they consulted Perplexity.ai for additional vocabulary or alternative expressions and decided whether these suggestions improved the clarity and coherence of their writing. (see Table 1).

Table 1

Experimental Group Activities

Unit	Writing Task	Use of Leo AR	Use of Perplexity AI
10	Feedback on company products	Students scanned product images to generate AR visualizations (3D models) for interactive review.	Used Perplexity to explore multiple review formats, compare tones, and analyze argument structures.
11	Personal story	Used AR objects (settings, events) to storyboard key narrative elements.	Brainstormed personal experiences and story arcs using AI-generated prompts.
12	Anecdote about a life lesson	Created AR maps of consequences and choices to explore different life decisions.	Discussed and compared various moral lessons and reflections with AI.

AI and AR tools were not used to check grammar but rather to support idea generation, multiple perspectives, questioning assumptions, and logical connections in writing. Each session involved a 20-minute exploration through AI and AR, a 20-minute brainstorming and planning, and a 20-minute drafting and revision.

For example, for Unit 12, the objective was that students write an anecdote about a personal experience that taught them a life lesson. The students followed the steps below for writing:

1. Warm-up discussion:
- Students discussed questions such as “Have you ever made a mistake that taught you something important?”
- Brainstormed ideas with their classmates.

2. AR engagement with Leo AR:
Students used the Leo AR camera to place and interact with 3D farm animals (e.g., cows, chickens, horses) in the classroom environment. They observed, described, and explained their experiences using 3D augmented pictures. On the basis of the AR experience, the students brainstormed a short story about a life lesson learned through an encounter with a farm animal.

3. AI Brainstorming with Perplexity:

The learner asked questions about writing strategies, explored ideas or structures for anecdotal writing, and provided suggestions for organizing their thoughts logically.

4. Writing phase:

Students drafted their anecdote using Perplexity AI to refine, question, and expand their ideas. Moreover, peer and teacher review and revision followed.

Control Group

The control group engaged in the same topics and instruction time but used traditional teaching methods without the combination of any AI or AR tools. The teacher followed standard classroom procedures for writing protocols, including brainstorming, model text, grammar focus, and peer/self/teacher review. For instance, in Unit 12, students were required to write an anecdote on the basis of a personal experience that taught them life advice. In this group, the activity was completed through several steps, including a pre-writing discussion. In this step, the teacher guided a class discussion about life lessons (e.g., the significance of honesty, learning from mistakes). The students discussed brief experiences orally in small groups. Second, model reading, in this phase, a sample anecdote was read from the textbook. The third section was a writing task; students planned their anecdotes utilizing a printed graphic organizer presented in the book. They were instructed to include a setting, the main event, and the life lesson. The last step was drafting and feedback. The students wrote their drafts on paper. Peer feedback was administered after the first draft was written. Each student exchanged their writing with a classmate and evaluated their writing on the basis of the book's instructions. The students provided handwritten comments or underlined unclear parts and discussed them in pairs. The teacher then provided written feedback focusing on content, organization, idea clarity, and coherence. Grammar feedback was minimal, as the focus was on meaning.

Post-Test Phase

The CCTST was administered in both the experimental and control groups as a post-test. Furthermore, to ensure that the post-test writing tasks indicated internalized critical thinking skills rather than tool-dependent performance, strict tool-free assessment protocols were used for both groups. In other words, all writing tasks were completed by hand under timed conditions. The post-test writing samples of both the experimental and control groups were analyzed via the Paul-Elder rubric, which focuses on critical thinking factors. The semi-structured interviews were used in the experimental group to explore their experiences with AI and AR in the writing process.

Qualitative Phase

The qualitative data were collected through a semi-structured interview protocol conducted in Persian with students in the experimental group at the end of the second month of study in the summer. The participants were informed that their data would remain confidential to address ethical considerations. Each interview lasted between 20 and 30 minutes, with all the experimental group participants' audio recordings transcribed for coding and analysis via thematic analysis. To ensure data credibility, the interview transcripts were shared with participants for verification. Once participants confirmed the accuracy of the transcripts, the credibility of the data was established. For dependability, 30% of the interview results were rechecked by two colleagues familiar with the data analysis process, and the inter-rater reliability was reported at 90% agreement. Themes emerged from Braun and Clarke's (2006) six-phase foundation for thematic analysis. The titling of themes and subthemes was based on the need to represent the underlying meaning of participants' responses as clearly as possible. The names were selected to indicate patterns of meaning across the data (e.g., semantic content and interpretative depth of students' experiences).

Data Analysis

The present study employed both quantitative and qualitative data analysis methods. With 33 participants, the study was powered at 80% ($\alpha = 0.05$) to detect large effects, demonstrating that smaller effects may not be reliably observed. The Shapiro–Wilk test was used to examine the normality of the

data, confirming that parametric tests were appropriate. ANCOVA was used to compare post-test results between the two groups while controlling for pre-test scores, to assess the true effect of the AI and AR-based interventions. In addition, an independent samples t-test was run to analyze the Paul-Elder critical thinking rubric scores. As the statistical analyses were specified a priori and directly corresponded to the predefined research questions, no adjustment for multiple testing was applied. In the qualitative phase, following Braun and Clarke's (2006) six-step approach, recurring patterns and themes were identified, offering deeper insights into students' perceptions of AI-assisted writing and its impact on their critical thinking disposition.

Results and Findings

Quantitative Step

Before the independent samples t-test was computed to compare the OPT results between the experimental and control groups, the assumption of normality was examined through the Shapiro-Wilk test. This test was employed because of its reliability in small sample sizes ($N < 50$). The results indicated that the distribution of OPT scores was normal in both groups, which allowed for the use of parametric statistical analysis (see Table 2).

Table 2

Shapiro-Wilk Test for Normality

Group	Statistic (W)	Sig.
Experimental	0.978	0.712
Control	0.968	0.489

Note. P-values > 0.05 indicate a normal distribution of OPT scores in both groups.

An independent samples t-test was used to determine whether there was a significant difference in OPT score between the two groups. The results revealed no statistically significant difference, indicating that both groups were homogeneous in English proficiency before the intervention. Table 3 presents the mentioned details.

Table 3

Independent-Samples t-test for OPT

Levene's Test F	Sig. (F)	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Diff.	Lower CI (95%)	Upper CI (95%)	Equal Variances Assumed
0.315	0.578	0.63	32	0.534	1.07	1.69	-2.42	4.56	Yes

Note. No significant difference in OPT score was found between the two groups ($p > 0.05$).

To confirm the appropriateness of the statistical procedures used in the current study, the assumption of normality was tested with the Shapiro-Wilk test across the primary variable (critical thinking). The results showed no deviations from normality ($p > 0.05$), supporting the use of parametric tests such as paired-samples t-tests. This initial confirmation of normality strengthens the reliability and validity of the subsequent statistical analyses (see Table 4).

Table 4

Tests of Normality

Group		Shapiro-Wilk		
		Statistic	df	Sig.
Experimental Group	Evaluation pre	0.795	16	0.102
	Evaluation post	0.784	16	0.112
	Inference pre	0.879	16	0.137
	Inference post	0.837	16	0.139
	Analysis pre	0.848	16	0.113

	Analysis post	0.869	16	0.126
	Deductive pre	0.896	16	0.069
	Deductive post	0.901	16	0.083
	Inductive pre	0.884	16	0.145
	Inductive post	0.882	16	0.141
	Total CCTST _pre	0.962	16	0.704
	Total CCTST _post	0.910	16	0.115
Control Group	Evaluation pre	0.819	17	0.105
	Evaluation post	0.882	17	0.142
	Inference pre	0.921	17	0.175
	Inference post	0.956	17	0.584
	Analysis pre	0.893	17	0.062
	Analysis post	0.870	17	0.127
	Deductive pre	0.917	17	0.151
	Deductive post	0.911	17	0.122
	Inductive pre	0.872	17	0.129
	Inductive post	0.902	17	0.087
	Total CCTST _pre	0.878	17	0.136
	Total CCTST _post	0.926	17	0.212
*. This is a lower bound of the true significance.				
a. Lilliefors Significance Correction				

The quantitative phase of the study was intended to examine the effects of Perplexity AI and the Leo AR app, combined with EFL writing activities, on learners' critical thinking skills. The descriptive statistics presented in Table 5 indicate an increase in the post-test mean scores in the experimental group on all subscales.

Table 5

Descriptive Statistics of the CCTST in Pre- and Post-test for the Experimental and Control Groups

Group			Mean	N	Std. Deviation	Std. Error Mean
Experimental Group	Pair 1	Evaluation pre	2.75	16	1.000	0.250
		Evaluation post	6.06	16	1.124	0.281
	Pair 2	Inference pre	2.63	16	1.025	0.256
		Inference post	6.50	16	1.211	0.303
	Pair 3	Analysis pre	1.56	16	1.413	0.353
		Analysis post	6.31	16	1.352	0.338
	Pair 4	Deductive pre	2.38	16	1.147	0.287
		Deductive post	5.63	16	1.310	0.328
	Pair 5	Inductive pre	3.25	16	1.000	0.250
		Inductive post	6.81	16	0.911	0.228
	Pair 6	Total CCTST _pre	12.56	16	3.326	0.832
		Total CCTST _post	31.38	16	3.722	0.930
Control Group	Pair 1	Evaluation pre	1.94	17	0.772	0.193
		Evaluation post	3.06	17	0.929	0.232
	Pair 2	Inference pre	3.00	17	1.155	0.289
		Inference post	4.50	17	1.265	0.316
	Pair 3	Analysis pre	1.81	17	1.377	0.344
		Analysis post	3.13	17	1.857	0.464
	Pair 4	Deductive pre	2.00	17	1.095	0.274
		Deductive post	3.13	17	1.088	0.272
	Pair 5	Inductive pre	3.19	17	0.834	0.209
		Inductive post	5.75	17	1.238	0.310
	Pair 6	Total CCTST _pre	12.25	17	2.646	0.661
		Total CCTST _post	19.56	17	2.502	0.626

To compare the post-test CCTST scores between the experimental and control groups while controlling for pre-test differences, ANCOVA was used. Before ANCOVA was computed, Levene's test of the equality of error variances was conducted, which demonstrated that the assumption of homogeneity of variances was met ($p > 0.05$). See Table 6 for details.

Table 6

Levene's Test of Equality of Error Variances

	F	df1	df2	Sig.
Evaluation post	1.595	1	31	0.216
Inference post	0.316	1	31	0.578
Analysis post	1.781	1	31	0.137
Deductive post	2.041	1	31	0.191
Inductive post	0.000	1	31	0.987
Total CCTST _post	2.441	1	31	0.127
Tests the null hypothesis that the error variance of the dependent variable is equal across groups.				
a. Design: Intercept + Evaluation pre + Inference pre + Analysis pre + Deductive pre + Inductive pre + Total CCTST _pre + Group				

According to Table 7, the ANCOVA outcomes demonstrated that there was a statistically significant difference between the experimental and control groups in the CCTST components, and the effect size suggested that Perplexity AI and Leo AR had a substantial positive effect ($F (1, 29) = 12.76$, partial $\eta 2 = 0.77$).

Table 7

Between-Group Comparisons of Post-test Using ANCOVA

Dependent Variable		Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Evaluation post	Contrast	43.319	1	43.319	11.763	0.000	0.605
	Error	28.280	24	3.682			
Inference post	Contrast	27.635	1	27.635	10.850	0.000	0.427
	Error	37.156	24	2.547			
Analysis post	Contrast	70.668	1	70.668	12.163	0.000	0.667
	Error	35.214	24	5.810			
Deductive post	Contrast	37.183	1	37.183	11.184	0.000	0.549
	Error	30.577	24	3.324			
Inductive post	Contrast	8.001	1	8.001	7.283	0.006	0.279
	Error	20.685	24	1.098			
Total CCTST _post	Contrast	865.861	1	865.861	12.765	0.000	0.769
	Error	260.523	24	67.830			

The F tests the effect of the group. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

To evaluate the final piece of writing in both groups, the Paul-Elder critical thinking writing rubric was used, which assesses written work on clarity, accuracy, precision, relevance, depth, breadth, logic, significance, and fairness. Two trained raters independently scored the writing pieces, and inter-rater reliability was measured to ensure scoring consistency. The total Cronbach's alpha was .88, indicating a high level of agreement between the raters (Experimental group = 0.89, Control group = 0.89).

On the basis of Table 8, the mean of the two raters' scores was utilized in the following independent-samples t-tests to compare the experimental and control groups' writing. Levene's test confirmed the assumption of equal variances for all the subscales. The experimental group indicated more total critical thinking factors ($t = 4.23$, $p < 0.001$). However, the results indicated no statistically significant difference in clarity scores between the experimental and control groups ($t = 1.98$, $p = 0.056$).

Table 8

Independent Samples Test for the Experimental and Control Groups Based on the Paul-Elder Critical Thinking Rubric

Sub-scales		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Clarity	Equal variances assumed	0.81	0.37	1.98	31	0.056	0.28	0.141	-0.01	0.57
	Equal variances not assumed.			2.01	3..02	0.052	0.28	0.139	0.00	0.56
Accuracy	Equal variances assumed	1.0	0.32	2.34	31	0.025*	0.48	0.206	0.06	0.90
	Equal variances not assumed.			2.32	29.9	0.026*	0.48	0.207	0.06	0.91
Precision	Equal variances assumed	0.78	0.38	2.21	31	0.034*	0.47	0.213	0.03	0.90
	Equal variances not assumed.			2.19	30.6	0.036*	0.47	0.215	0.03	0.91
Relevance	Equal variances assumed	1.14	0.29	2.96	31	0.006**	0.53	0.179	0.16	0.90
	Equal variances not assumed.			2.99	30.9	0.005**	0.53	0.177	0.17	0.89
Depth	Equal variances assumed	0.92	0.34	2.78	31	0.009*	0.88	0.317	0.23	1.53
	Equal variances not assumed.			2.81	30.4	0.008**	0.88	0.313	0.24	1.52
Breadth	Equal variances assumed	0.63	0.43	2.15	31	0.0039*	0.44	0.204	0.02	0.86
	Equal variances not assumed.			2.12	29.6	0.0041*	0.44	0.206	0.01	0.86
Logic	Equal variances assumed	1.02	0.32	3.42	31	0.002**	1.04	0.304	0.42	1.66

	Equal variances not assumed.			3.45	30.1	0.002**	1.04	0.302	0.43	1.65
Significance	Equal variances assumed	0.89	0.35	2.86	31	0.007**	0.94	0.328	0.27	1.61
	Equal variances not assumed.			2.83	30.8	0.008**	0.94	0.332	0.26	1.62
Fairness	Equal variances assumed	1.09	0.30	3.88	31	0.001**	1.09	0.281	0.52	1.66
	Equal variances not assumed.			3.91	30.5	0.001**	1.09	0.279	0.53	1.65
Total	Equal variances assumed	1.21	0.28	4.23	31	0.000*	1.16	0.274	0.60	1.72
	Equal variances not assumed.			4.26	30.8	0.000*	1.16	0.272	0.61	1.71

Qualitative Step

A qualitative phase was conducted with the students in the experimental group. The interviews aimed to gain a deeper understanding of the nuances and subjective aspects of students' engagement with AI- and AR-mediated instruction. For this purpose, thematic analysis was used to identify the themes that emerged, reflecting the rich perceptions of the students. The analysis revealed five major themes: *AI and AR as imagery stimuli for ideas and enhancing content development; structured support for reasoning; enhanced cognitive engagement; confidence and ownership; and overreliance on technological tools.*

Theme 1. AI and AR as Imagery Stimuli for Idea Making and Enhancing Content Development

As students mentioned, through Perplexity AI, they could write on the basis of new understanding and enrich content with various perspectives. They also highlighted that they could connect AR images to real-life situations, developing narrative depth. Moreover, they could define personal memories or life experiences through AR with their peers.

Subtheme 1.1. Enhancing the Logical Flow of Events

One expressed that "I could imagine where each part of the story would go, like a movie, because I could see it, and by AI, I could write about examples that I had not considered".

Subtheme 1.2. AI is Better for Organization, and AR is Better for Brainstorming

"Leo helped me think creatively, and Perplexity helped me organize." Stated by some students in the experimental group. Some others explained, "I preferred AI more for academic writing and AR for creativity".

Subtheme 1.3. Engagement and Motivation

The students clarified that AI and AR tools increased their willingness to write more because of the interactive nature of such tools. “I wanted to describe everything I saw through AR and write about different aspects of any topic that I discussed with AI”.

Theme 2. Structured Support for Reasoning

This theme clarifies how students believe that Perplexity AI and Leo AR tools facilitate scaffolding or cognitive patterns that assist them in reasoning through their ideas more clearly, thoroughly, and critically while writing.

Subtheme 2.1. Clarifying General Ideas

“I had an idea, but perplexity helped me make it stronger and clearer”. Mentioned by some students in the experimental group.

Subtheme 2.2. Filling the Reasoning Gap

Learners used AI suggestions to complete their argument. As mentioned by one, “When I wanted to write about a topic, I ordered my opinions, then, through using AI, I found the gap in my ideas and more information about different aspects of that topic”.

Theme 3. Enhanced Cognitive Engagement

This emerging theme refers to the learners’ increase in mental effort, sustained attention, and deeper interaction with content while using AI and AR tools during writing activities. It highlights how technology promotes active thinking, questioning, and decision-making processes, which are the main tenets of critical thinking.

Subtheme 3.1. Idea Generation and Expansion

“Leo AR helped me come up with more things to say when I saw the scenes”.

Subtheme 3.2. Enriching Content with Various Perspectives

Students highlighted that Perplexity AI paved the way for them to consider different dimensions of topics: “I could write more and think of various aspects of any topic with AI”.

Subtheme *3.3. Cognitive Curiosity and Exploration*

Learners explained that using AI encouraged them to ask more “what if” or “why” questions. For instance, AI-generated ideas provoked curiosity in exploring more explanations or added complexity to their writing.

Theme 4. Confidence and Ownership

AI and AR tools gave learners a sense of improvement and independence, and increased confidence in their ability to write.

Subtheme *4.1. Sense of Agency and Autonomy*

The students reported making their decisions rather than relying on the teacher's knowledge: “It helped me, but I chose what to keep. That made me feel it was my own work”.

Subtheme *4.2. Motivation to Revise Critically*

Students were more willing to revise and improve their writing frequently. As said by some, “I wanted to make my writing better, and I could see where I went wrong. I revised it twice”.

Theme 5. Overreliance on Technological Tools

Some students mentioned that they waited for AI and AR tools to start writing rather than finding new ideas independently. This indicated a reduction in independent thinking.

Subtheme *5.1. Reduced Independent Thinking*

Students relied on Perplexity AI rather than making their own ideas or opinions. “I did not think much myself. I just followed what Perplexity said; it seemed better than I”. And one more, “I copied the sentences because they were more advanced than what I could write”.

Subtheme *5.2. Passive Engagement*

Instead of actively making their reflections and ideas, some students became passive consumers of AI productions: “I waited for Perplexity and Leo AR to give me an idea. I did not brainstorm like I usually do”.

Discussion

The current study examined the synergistic effects of generative AI via Perplexity and AR via Leo AR on critical thinking in EFL writing. Furthermore, this study aimed to investigate EFL learners’ perceptions of how AR and AI tools influence their critical thinking during writing activities. The findings revealed a remarkable improvement in the experimental group's critical thinking scores, as computed by the Paul-Elder rubric and CCTST, compared with those of the control group. These outcomes demonstrate that the integration of AR and AI can meaningfully improve higher-order thinking skills in language learners, especially in writing tasks. The participants in the experimental group not only indicated statistically higher mean scores in the post-test writing but also demonstrated deeper levels of reflection and argument organization during the qualitative interviews. The engaging and autonomous nature of AI and AR tools might be a reason for better outcomes in favor of the experimental group. In this research, clarity, as a key aspect of writing, did not significantly differ between the experimental and control groups, unlike the other dimensions of the Paul-Elder critical thinking framework. This might be related to learners perceiving that AI can produce more grammatical sentences; therefore, there may be less need to correct AI-generated content.

Thematic analysis of interviews with the experimental group illustrated learner perceptions regarding AI and AR-powered tasks. The students reported that the supportive nature of AI enhanced their motivation and confidence in writing. Moreover, they expressed the benefits of reducing anxiety and encouraged writing fluency through the use of AI. Learners also mentioned that AR could facilitate idea generation. Wang’s (2025) quantitative results indicate that the assimilation of an AI-supported tool mainly decreases learners’ anxiety and significantly increases their pleasure in learning. Moreover, the results revealed an important improvement in the overall English proficiency level of the experimental group compared with that of the control group. In a study, Alruwaili and Kianfar (2025) reported that teachers who participated in an interview highlighted the role of AI in improving their competence to convey individualized direction and govern classrooms more dexterously. Chang et al.’s (2020) findings show the positive effects of AR learning on learners’ concentration, satisfaction, confidence, and learning effectiveness. Khan et al. (2023) focused on the impacts of AR on learners’ vocabulary learning. The results indicated higher post-test scores in the experimental group, but no important differences were observed in the delayed post-test. The findings also illustrated that AR helped learners improve their vocabulary with better comprehension. The combination of AI and AR tools is beneficial for scaffolding and idea generation, but it might limit learners' independent critical reflection, as they may rely more on recommendations or outputs from these platforms. As Elder and Paul (2012) assert, critical thinking in writing needs more than correct grammar or structure; it involves active intellectual engagement, which may not occur unless one is intentionally trained.

The integration of Leo AR and Perplexity AI proved effective in this study because each tool complements different but essential aspects of the writing and thinking processes in the EFL context. Their combined use enhances idea generation and cognitive engagement, which are crucial for developing advanced writing skills. Perplexity AI acts as a generative conversational tool that offers

learners real-time feedback, contextual information, and alternative viewpoints. This aligns with Vygotsky's concept of ZPD (1978), as AI helps learners improve their ability to form and justify opinions more critically. AR supports visual learning and experiential immersion, enabling learners to interact with content in a dynamic, context-rich environment. This research, with consistent results in the literature, demonstrates the usefulness of AI in providing personalized feedback and adaptive learning methods, contributing to improved critical thinking. Park and Doo (2024), in a systematic literature review, noted the positive effect of AI tools on learners' autonomy and independence during learning. According to their review, numerous studies have introduced AI as an assistant that fosters affective communication with learners and accelerates the learning process. Similarly, Wu (2024), in a meta-analysis, reported that AI-integrated learning not only enhances listening and speaking skills but also improves writing and vocabulary acquisition. Wu et al. (2013) indicated that AR visualization makes ideas more concrete, which is especially helpful in narrative and descriptive writing tasks. The findings support Bacca et al. (2014), who highlight that AR enhances learners' engagement and improves contextual understanding by integrating virtual content with the real world.

In contrast, some findings illustrate the dependency on AI suggestions and passive engagement with tasks. Octaberlina et al. (2024) noted that AI threatens critical thinking in academic writing by reducing active engagement, inhibiting creativity, and increasing dependency, which ultimately decreases individual thinking skills and uniqueness, leading to negative effects on writing quality in EFL contexts. Furthermore, Darwin et al. (2024) warned about the overreliance on AI tools that can threaten learners' critical thinking and decrease their engagement in the writing process. This finding aligns with that of Ju (2023), who mentioned the negative impact of overreliance on AI on learners' reasoning skills.

Conclusion and Implications

By examining the effects of AI and AR on critical thinking in EFL writing, the results of this research revealed the profound influence of Perplexity AI and Leo AR on these variables. Unlike its promising outcomes, this study is not without limitations. First, the sample size was relatively small (N = 33), which limits the generalizability of the findings. Second, the intervention lasted only two months, which may not account for the long-term impacts. Third, individual differences such as learner motivation were not fully controlled, possibly influencing the results. This study may contribute to a growing body of literature on multimodal approaches in language education by demonstrating that combining AR and AI tools can enhance critical thinking in EFL writing. The combination of Leo AR and Perplexity AI offers a novel, interactive context for learners to visualize ideas, receive real-time feedback, and reflect critically on their writing. The findings provide valuable insights for language instructors seeking to enrich writing instruction through technology-enhanced learning environments. Furthermore, in alignment with Wu et al.'s (2013) findings, the research suggests that intermediate learners, who often have problems with writing tasks, benefit from AR to encourage imagination and AI assistance to refine and develop their ideas. Future research should consider several recommendations, such as employing larger samples to increase generalizability, conducting longitudinal research, and exploring the role of learner agency in mediating the effectiveness of technological tools.

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Declaration of Conflicting Interests

The authors declare that they have no conflict of interest.

Ethical Considerations

Before data collection, the participants were informed that they were part of a research study. Informed consent was obtained from all participants and parents. The participants were assured that their responses would remain confidential and anonymous and that the data would be used only for research purposes.

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