The Effectiveness of Virtual Digital Human Pedagogical Agents in Virtual Reality Learning Environments: A Meta-Analysis of 36 Empirical Studies

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Abstract

Virtual Digital Human Pedagogical Agents (VDHPAs) have emerged as vital tools in online and blended learning environments. However, the extent to which they improve learning outcomes in Virtual Reality (VR) environments remains inconclusive. This meta-analysis synthesizes findings from 36 empirical studies conducted between 2013 and 2023 to examine the effectiveness of VDHPAs in VR-based learning. Specifically, we analysed two process-oriented variables—cognitive load and social presence—and three outcome-oriented variables—retention, transfer, and other assessment types. The results indicate that while VDHPAs do not significantly reduce cognitive load (g = -0.084), they significantly enhance learners' social presence (g = 0.402). Additionally, VDHPAs were found to improve retention (g = 0.451), transfer (g = 0.288), and other test scores (g = 0.423). Moderator analyses revealed that the effects vary depending on agent design features (e.g., gestures, voice, facial expression), content characteristics (e.g., subject domain, knowledge type), and learner attributes (e.g., education level, prior knowledge). This review further discusses the implications of agent embodiment, the "uncanny valley" in affective response, and challenges in long-term outcome assessments. The study contributes to a deeper understanding of how to optimise VDHPAs for immersive learning experiences and highlights directions for future interdisciplinary research in educational technology and digital arts.

Keywords: Virtual Reality; Virtual Digital Human; Pedagogical Agent; Meta-analysis; Learning Outcomes; Cognitive Load; Social Presence; Educational Technology

1. Introduction

The rapid convergence of virtual reality (VR), computer graphics, speech synthesis, and emotion modelling has accelerated the evolution of Virtual Digital Human Pedagogical Agents (VDHPAs) as intelligent learning companions. The development of humanoid robots such as Ameca, powered by GPT-3 and now tested with GPT-4, exemplifies this trend. These agents are increasingly deployed in VR learning environments to simulate real-time human interaction, offering instructional guidance while alleviating teachers' workload.

Despite their growing use, the effectiveness of VDHPAs in VR remains a subject of debate. While some researchers claim that these agents can increase learners' engagement and achievement through heightened social presence, others argue they may induce cognitive or emotional interference, particularly when their design fails to meet learner expectations.

Drawing on theories such as the Persona Effect, Social Presence Theory, and Social Agency Theory, this review examines whether VDHPAs enhance learning by fostering social cues and reducing cognitive burden. Conversely, we also explore concerns rooted in Cognitive Load Theory and the "uncanny valley" phenomenon, suggesting that overly anthropomorphic agents may impede learning by generating distraction or discomfort.

This study aims to address the gap in existing literature by systematically analysing empirical studies that integrate both VR environments and VDHPAs. We explore how agent design features, instructional content, and learner differences moderate learning processes and outcomes. By doing so, this meta-analysis provides evidence-based recommendations for optimising agent-based instruction in immersive environments.

2. Literature Review

2.1. Key Concepts

2.1.1. Virtual Reality Learning Environments

Virtual reality (VR) learning environments offer highly immersive experiences that promote learners' subjective initiative. With a rich array of constructive tools and expression platforms, VR aligns with Piaget's vision of "bringing the laboratory into the classroom" and the constructivist idea that "learning is the experience of authentic contexts." Burdea and Coiffet summarised the core characteristics of VR as the "3I" features: Interaction, Immersion, and Imagination. "Reality" in VR refers to objects or scenes that exist physically or functionally, whether in the real world or simulated through digital means. These attributes allow VR to visualise and enable complex data interaction, fostering situated, experiential learning.

2.1.2. Virtual Digital Humans

Virtual digital humans aim to replicate human-like digital representations through computer graphics (CG), endowed with specific identities and behavioural traits to reduce psychological distance between the agent and the learner. According to the 2020 White Paper on Virtual Digital Human Development (Yan et al., 2020), a virtual digital human (hereafter "digital human") is defined as a virtual character with a digitised appearance. Unlike physical robots, digital humans exist via display devices and typically possess the following features:

(1) A human-like appearance with defined facial characteristics, gender, and personality traits;

(2) Human-like behaviour, including the ability to communicate via language, facial expressions, and gestures;

(3) Human-like cognition, enabling recognition of the external environment and interaction with users.

The white paper highlights their visual characteristics but does not fully define the concept's cognitive dimensions.

2.1.3. Pedagogical Agents

Pedagogical agents refer to digital characters designed to support instruction in online or blended learning environments. They often appear as conversational agents, interacting through speech, gestures, and facial expressions. These agents are embedded within the learning process to provide cognitive scaffolding and promote sociocultural engagement. Beyond supplying resources and responding to questions, they can simulate teacher-like guidance, encourage learners, and reduce negative emotions such as anxiety and confusion. Earlier intelligent tutoring systems focused on cognitive functions; modern pedagogical agents extend to socio-cultural domains and can act as teaching assistants, mentors, experts, or peer learners.

2.2. Theoretical Framework

2.2.1. Theoretical Assumptions Supporting the Effectiveness of VDHPAs in VR Learning Environments

A review of existing research reveals several theoretical models that support the learning-enhancement potential of Virtual Digital Human Pedagogical Agents (VDHPAs) in VR environments. These include the Persona Effect, Social Presence Theory, and Social Agency Theory.

The Persona Effect suggests that the mere presence of a virtual pedagogical agent in a learning environment — regardless of its expressive capabilities — can positively influence learners' perceptions of the learning process. In other words, even minimally expressive agents can improve the learning experience simply by personifying instructional content in a VR context.

Social Presence Theory explains how the perceived presence of others—teachers or peers—in virtual environments can enhance learners' engagement and satisfaction. It postulates that when learners feel a sense of real human presence, even via digital avatars, they are more likely to develop positive learning experiences. Initially developed to study the communicative effects of electronic media, this theory has since been extended to educational contexts, demonstrating that increased social presence can elevate learning satisfaction and engagement. In VR learning environments, integrating VDHPAs can increase learners' sense of presence, which in turn can boost motivation, reduce perceived task difficulty, and lower mental effort.

Social Agency Theory — sometimes referred to as the "social cues hypothesis" — offers a detailed explanation of how pedagogical agents impact learning outcomes. It posits that social cues emitted by VDHPAs (e.g., facial expressions, gestures, voice) can trigger social responses from learners. Learners treat these agents as social partners, prompting them to apply deeper cognitive processing strategies to understand instructional content. These strategies involve selecting relevant information, organizing fragmented ideas, and integrating them into coherent mental models, ultimately enabling better retention and transfer of knowledge. The theory concludes that adding social agents to multimedia learning environments enhances learning outcomes, particularly in transfer tasks.

Each of these theories explains different aspects of how VDHPAs enhance learning. The Persona Effect highlights the importance of human-like representation; Social Presence Theory focuses on improved learning perception through heightened presence; and Social Agency Theory emphasizes deep cognitive engagement stimulated by social interaction cues.

2.2.2. Theoretical Assumptions Regarding the Potential Hindrances of VDHPAs in VR Learning Environments

While many studies highlight the benefits of VDHPAs, others suggest that they may hinder learning due to cognitive and emotional interference. This view draws upon Cognitive Theory of Multimedia Learning, Cognitive Load Theory, and Interference Theories of Social Agency.

From a cognitive perspective, VDHPAs may act as distractions by overloading learners' attention. According to the Cognitive Theory of Multimedia Learning, human cognitive architecture includes two limited-capacity channels — visual and auditory. In VR, the visual channel must process both learning materials and non-verbal cues from the agent (e.g., facial expressions, gestures), which may introduce extraneous cognitive load.

Cognitive Load Theory argues that when learners' cognitive resources are allocated to process irrelevant visual cues from the agent, fewer resources are available for processing essential learning content, thereby reducing learning efficiency. Expanding on this, Interference Theory posits that VDHPAs, when irrelevant to the learning objective, may divide learners' attention—a phenomenon known as the split-attention effect. This occurs when learners simultaneously interpret instructional content and agent behaviours, potentially overwhelming working memory and impairing retention and transfer performance.

Emotionally, VDHPAs may also provoke negative reactions. Although learners may initially feel positively toward highly human-like digital agents, unmet expectations due to technological limitations can cause frustration or discomfort. This parallels the Uncanny Valley Hypothesis, which posits that when a robot or virtual agent closely resembles a human but falls short in subtle ways, it may trigger aversion rather than empathy.

2.2.3. Potential Boundary Conditions in VDHPAs' Effectiveness

The inconsistent findings in existing research on VDHPAs in VR learning environments may stem from unaccounted moderating variables. We categorize these potential moderators into four domains: characteristics of the VR environment, features of the pedagogical agent, learning content, and learner characteristics.

VR Environment Features: Based on the "3I" framework—Immersion, Interactivity, and Imagination—VR enhances concentration, learner engagement, and context-based understanding, making it a fertile environment for educational experiences.

VDHPA Features: These include the agent's visual appearance, gestures, facial expressions, and voice. Learners' preferences regarding these traits can significantly affect the agent's instructional effectiveness. For example, gestures enhance instructional clarity, facial expressions serve as strong social cues, and natural human voice improves learner engagement more effectively than synthesized speech.

Learning Content Features: The effectiveness of VDHPAs may also depend on subject matter (e.g., STEM vs. non-STEM), knowledge type (e.g., declarative vs. procedural), and instructional pacing (system-paced vs. learner-paced). Declarative knowledge (facts and concepts) may be easier to convey through agents than procedural knowledge (skills and problem-solving).

Learner Characteristics: These include educational level and prior knowledge. Prior knowledge, in particular, is a known moderator in multimedia learning. For example, instructional designs that benefit novice learners may hinder advanced learners—a phenomenon known as the expertise reversal effect.

2.3. Overview of Existing Research

Over the past decade, more than 18 review articles and meta-analyses have been published investigating either the efficacy of Virtual Reality (VR) in education or the pedagogical value of Virtual Digital Human Pedagogical Agents (VDHPAs). However, few of these studies have examined the combined effect of VDHPAs within VR learning environments. Most existing analyses focus either on the effectiveness of pedagogical agents in general, or on the instructional potential of VR technology alone.

The primary variables evaluated in these prior studies include characteristics of the pedagogical agents (e.g., appearance, gestures, voice), learner-related factors (e.g., educational level, learning style), and instructional conditions (e.g., subject domain, pacing). Table 1 below summarises the five most recent and representative meta-analyses published between 2013 and 2023, listing the variables examined and the outcome indicators.

Table 1. Summary of Meta-Analytic Variables Examined in Recent VDHPAs Studies (2013–2023)

Study	No. of Articles	Time Span	Agent Features	Other Variables	Outcome Variables
Gu (2015)	23	2002–2013	Emotional vs. Non-emotional agents	–	Learning motivation; Retention; Transfer

Wang et al. (2017)	32	2000–2015	Voice type (human, computer-generated, none); Gesture (present/absent); Agent type (human/animal)	Subject domain; Pacing; Learner group	Motivation, Interest, Retention, Transfer, Other tests
Davis (2018)	17	2001–2016	Gesture types (deictic, emblematic, metaphoric); Voice (human/computer); Agent type (human-like/animated)	Domain, Educational level, Time exposure	Retention; Transfer; Cognitive load
Castro-Alonso et al. (2021)	21	2012–2019	Appearance (2D/3D); Gender; Gesture; Facial expression; Voice type	Domain, Subject, Education level, Language, Nationality	Learning outcomes
Wang Xue et al. (2022)	39	2011–2021	Gender, Role (peer/expert), Presentation (2D/3D), Actions (gesture/facial), Feedback type (verbal/non-verbal)	Knowledge type, Education stage, Emotion	Learning outcomes

These meta-analyses primarily examined how variations in agent design influence learning outcomes, with some studies incorporating moderator analyses based on content domain and learner characteristics. Substantive findings and design recommendations have emerged from this literature, although results remain mixed due to inconsistencies in study designs, measurement tools, and sample representativeness.

Notably, studies conducted before 2016—before the so-called "AI boom"—largely focused on simple information presentation tasks using agents with limited interactivity. Furthermore, methodological shortcomings such as non-randomised samples or low experimental fidelity have contributed to inconclusive results in early literature.

This present study builds upon these earlier efforts by systematically reviewing and conducting a meta-analysis on 36 empirical studies published between 2013 and 2023. Specifically, it investigates how VDHPAs affect learning processes (cognitive load and social presence) and learning outcomes (retention, transfer, and other assessments) when used in immersive VR environments. By examining a broader set of moderators—including agent design, instructional content, and learner characteristics—this study aims to provide more reliable conclusions and evidence-based guidance for the future development of VDHPAs in VR learning environments.

2.4. Research Questions

This review aims to examine the empirical studies published over the past decade that investigate the effects and limitations of using Virtual Digital Human Pedagogical Agents (VDHPAs) in Virtual Reality (VR) learning environments. The analysis focuses on two dimensions: learning process variables (i.e., cognitive load and social presence) and learning outcome variables (i.e., retention, transfer, and other assessment types), to determine whether VDHPAs contribute to improved learning within immersive VR contexts.

Given that the effectiveness of VDHPAs may be influenced by various moderating factors—including agent-related features, instructional material characteristics, and learner attributes—this study also incorporates moderator analyses to identify potential boundary conditions.

Accordingly, the research is guided by the following questions and hypotheses:

(1) Can VDHPAs in VR learning environments reduce learners' cognitive load and enhance their sense of social presence?
(2) To what extent do VDHPAs improve learners' academic performance in terms of retention, transfer, and other test outcomes?
(3) Are the effects of VDHPAs on learning outcomes moderated by factors such as agent characteristics (appearance, gestures, facial expressions, voice), learning material properties (subject domain, knowledge type), and learner features (learning pace, education level, prior knowledge)?

3. Methodology

3.1. Research Approach

This study adopts a meta-analytic methodology in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The objective is to quantitatively synthesise empirical research findings on the effectiveness of Virtual Digital Human Pedagogical Agents (VDHPAs) in VR learning environments. Data such as sample size, means, and standard deviations were extracted from eligible studies for effect size calculation. Meta-analysis is a robust statistical technique that integrates previous empirical research through systematic, quantitative methods, typically involving the following procedures:

(1) defining the research objective;
(2) conducting comprehensive literature searches;
(3) determining inclusion criteria;
(4) coding key variables;
(5) identifying statistical features of the studies;
(6) compiling and entering data;
(7) performing statistical analysis using appropriate models.

3.2. Literature Search Strategy

The literature search covered the period from January 2013 to April 2023, with a focus on English-language empirical studies involving VDHPAs in VR learning environments. The databases consulted included Web of Science, ScienceDirect, Springer, Education Research Complete, ProQuest, and Wiley. Search queries combined terms such as "virtual reality," "VR" with "virtual human," "digital people," "pedagogical agent," "agent," "intelligent mentor," "virtual character," "teaching incarnation," and "educational agents," along with educational keywords like "learning," "teaching," "student," "learner," and "learning environment."

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To ensure completeness, backward reference checking and Google Scholar supplementation were also conducted.

3.3. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

(1) Empirical research methodology was employed (non-empirical studies were excluded);
(2) The study took place within a VR learning environment (traditional classrooms or non-VR settings were excluded);
(3) The research explicitly examined the effects of VDHPAs on learning outcomes in VR contexts;
(4) A control group without VDHPAs was included to enable comparative analysis;
(5) At least one of the dependent variables related to learning process (e.g., cognitive load, social presence) or outcomes (e.g., retention, transfer) was measured;
(6) Complete data were available to compute effect sizes—acceptable formats included (a) means, standard deviations, and sample sizes; (b) means, t-values, and sample sizes; (c) means, p-values, and sample sizes; or (d) mean differences, pooled SD, and sample sizes.

The initial search identified 155 articles. After removing duplicates and irrelevant studies based on title and abstract screening, 76 papers remained. A final eligibility assessment based on full-text review yielded 36 empirical studies suitable for inclusion in the meta-analysis.

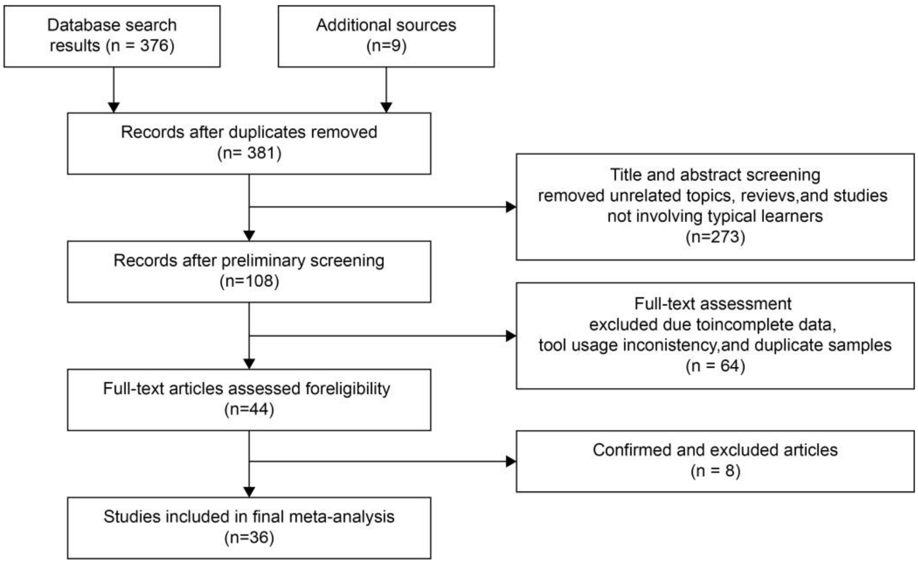

Figure 1. Flow chart of Study Selection Process

3.4. Research Tools, Effect Size Metrics, and Model Selection

Comprehensive Meta-Analysis (CMA) software version 3.0 was used for data analysis. Given that different studies reported continuous outcomes with varied units, Hedges's g was selected as the primary effect size metric. This metric corrects for potential upward bias in Cohen's d due to small sample sizes by applying a standardised mean difference multiplied by a correction factor.

Two statistical models are commonly used in meta-analysis: the Fixed Effects Model and the Random Effects Model. If heterogeneity among studies is minimal, the Fixed Effects Model is preferred. However, when heterogeneity is substantial, the Random Effects Model is recommended. In this study, given the diversity in knowledge types, agent types, and participant backgrounds, the Random Effects Model was deemed more appropriate for estimating overall effects. Sensitivity analyses were also conducted to assess heterogeneity sources.

3.5. Coding Procedure

To ensure consistency across studies, all included research was systematically coded according to a standardised framework. The coding process encompassed four major categories: basic study information, agent characteristics, instructional features, learner characteristics, and outcome variables. The criteria for each coding dimension are summarised in Table 2.

Table 2. Coding Scheme for Included Studies

Category	Variable	Code Options
Basic Information	Author	Author(s) of the study
	Publication Year	Year of publication
	Publication Type	Journal article / Conference paper
	Sample Size	Total number of participants
Agent Characteristics	Appearance	Human-like / Anthropomorphic
	Gesture	Present / Absent[1]
	Facial Expression	Expressive / Non-expressive
	Voice Type	Human voice / Computer-generated / None
Instructional Features	Subject Type	General (theoretical) / Practical (applied)
	Knowledge Type	Declarative / Procedural
Learner Characteristics	Learning Pace	Learner-paced / System-paced
	Education Level	Primary / Secondary / Adult learners
	Prior Knowledge	Low / High
Outcome Variables	Process Indicators	Cognitive Load / Social Presence
	Learning Outcomes	Retention / Transfer / Other test outcomes

*Gestures were assumed present unless explicitly stated otherwise, or coded as absent when only a headshot of the agent was shown.

Table 3. Summary of Effectiveness of VDHPAs in VR Learning Environments: Meta-Analytic Overview

Study	Type	Sample Size	Appearance	Gesture	Facial Expression	Voice	Subject Type	Knowledge Type	Learning Pace	Education Level	Prior Knowledge	Process Variable	g(Process)	Outcome Variable	g(Outcome)
Chiquet, 2023	J	66	P	-	-	-	GC	D	L	AD	-	SP	1.133, 0.219	-	-
Chiquet, 2023	J	58	P	-	-	-	GC	D	L	AD	-	-	-	O	-0.011
Barrett, 2023	J	10	P	G	NE	-	PL	D	L	AD	H	-	-	O	0.443
Tai, 2022	J	49	P	G	NE	M	GC	P	L	MD	H	-	1.028	RT	0.871
Tai, 2022	J	49	P	G	NE	M	GC	P	L	MD	H	-	-	O	1.198, 0.170
Tai, 2022	J	49	P	G	NE	M	GC	P	L	MD	H	-	-	RT	0.867, 0.668
Abril, 2022	J	53	P	-	-	-	GC	P	S	AD	-	SP	1.535, 1.941	-	-
Horovitz, 2021	J	112	P	G	E	-	GC	P	S	AD	L	CL	-0.585	TT	-0.177, 0.148
Ba, 2021	J	62	P	NG	E	M	GC	P	S	AD	-	CL	-0.384	TT	0.771
Seymour, 2021	J	162	P	G	E	M	GC	D	L	AD	-	-	-	O	0.322

Shalmani, 2021	J	120	P	G	E	-	GC	D	S	AD	-	-	-	RT	2.041, 1.934
Grivokostopoulo, 2020	J	114	P	G	E	-	PL	P	L	AD	L	-	-	TT	1.526
Lin, 2020	J	96	P	NG	NE	M	GC	D	L	AD	L	CL	0.441	RT & TT	0.098, -0.027
Lin, 2020	J	96	P	NG	NE	M	GC	D	L	AD	L	CL	-0.432	RT & TT	-0.109, -0.050
Schmidt, 2019	J	24	P	G	E	M	GC	D	L	AD	L	SP	0.303	-	-
Li, 2019	J	123	P	G	NE	-	GC	P	S	AD	L	-	-	RT & TT	1.119, 0.799
Li, 2019	J	123	P	G	NE	-	GC	P	S	AD	L	-	-	RT & TT	1.122, 1.133
Davis, 2019	J	183	P	G	E	-	GC	D	S	AD	L	SP	0.333, 0.268	RT	0.372, 0.586
Fountoukidou, 2019	J	99	P	NG	NE	M	GC	D	S	AD	L	-	-	RT	0.230
Makransky, 2019	J	66	P	G	E	M	PL	P	S	MD	L	SP	-0.157	RT & TT	0.653, 0.903
Makransk	J	66	P	G	E	M	PL	P	S	MD	L	SP	0.748	RT & TT	-0.435,

y, 2019															-0.223
Nye, 2018	J	76	P	NG	-	-	GC	P	S	AD	-	-	-	TT & O	0.045, 0.192
Kyrlitsias, 2018	J	52	P	G	NE	H	PL	D	L	AD	L	SP	0.621	O	0.804
Nielen, 2018	A	-	-	-	H	GC	D	S	PD	L	-	-	RT	0.320, 0.137	
Bringula, 2018	J	60	P	G	E	-	GC	P	S	MD	H	-	-	RT	0.573
Craig, 2017	J	140	P	-	-	H	GC	P	S	AD	-	-	RT & TT	0.029, -0.017	
Tegos, 2017	J	72	P	NG	-	-	GC	D	S	AD	L	SP	0.559, 0.296	TT	0.642, 0.920
Davis, 2017	J	160	P	G	NE	H	GC	D	L	PD	L	SP	0.274	RT & TT	-0.104, 0.060
Davis, 2017	J	160	P	G	NE	H	GC	D	L	PD	H	SP	0.052	RT & TT	0.062, 0.374
Beege, 2017	J	42	P	G	NE	N	GC	D	S	AD	L	CL	-0.141	RT & TT	0.412, 0.186
Beege, 2017	J	42	P	G	NE	N	GC	D	S	AD	L	CL	0.465	RT & TT	0.240, 0.060

Webster, 2016	J	140	P	G	-	-	PL	D	L	AD	L	-	-	RT	0.148, 0.604
Guo, 2016	J	159	A	G	E	-	GC	P	S	AD	H	-	-	RT & O	0.085, 0.572
Carlotto, 2016	J	72	P	G	E	H	GC	D	S	AD	H	-	-	RT	0.373
Huang, 2016	J	54	P	NG	-	-	GC	P	S	AD	L	CL & SP	-0.222, 0.414	RT & TT	0.619, 0.273
Liew, 2016	J	107	P	-	E	M	GC	P	S	AD	L	SP	0.349, 0.046	TT	0.185

*Note: P = Human-like agent; A = Anthropomorphic agent; G = Gesture present; NG = No gesture; E = Expressive; NE = Non-expressive facial expression; M = Machine-synthesised voice; H = Human voice; N = No voice; GC = General course; PL = Practical learning; P = Procedural knowledge; D = Declarative knowledge; L = Learner-paced; S = System-paced; AD = Adult learners; MD = Mid-level learners; PD = Primary learners; L = Low prior knowledge; H = High prior knowledge; CL = Cognitive Load; SP = Social Presence; RT = Retention test; TT = Transfer test; O = Other test types; '-' = Not measured or not reported.

The Table 3 summarises 36 empirical studies analysed in this meta-review, detailing each study's publication type, sample size, agent features, learning conditions, learner profiles, and outcome measures.

To minimize the impact of publication bias on our study conclusions, we employed two methods for testing and correction. First, we systematically reviewed and screened both published and unpublished literature in relevant fields to ensure the comprehensiveness and representativeness of the sample. During the screening process, we paid attention not only to positive results that support the hypothesis but also to neutral or negative results that did not meet expectations, to avoid one-sided interpretations of the research findings.

Secondly, we used the funnel plot (see Figure 2) as an intuitive tool to visually assess publication bias. In the funnel plot, we plot the effect size (such as the magnitude of the effect) of each study on the x-axis and the measurement of its precision (such as sample size) on the y-axis. Theoretically, if there is no publication bias, the data points for each study should show a symmetrical distribution resembling an inverted funnel. Conversely, if the graph shows asymmetry, it may indicate the presence of publication bias. Through the examination of the funnel plot, we confirmed that the sample selected for this study was free from significant bias and had high research precision.

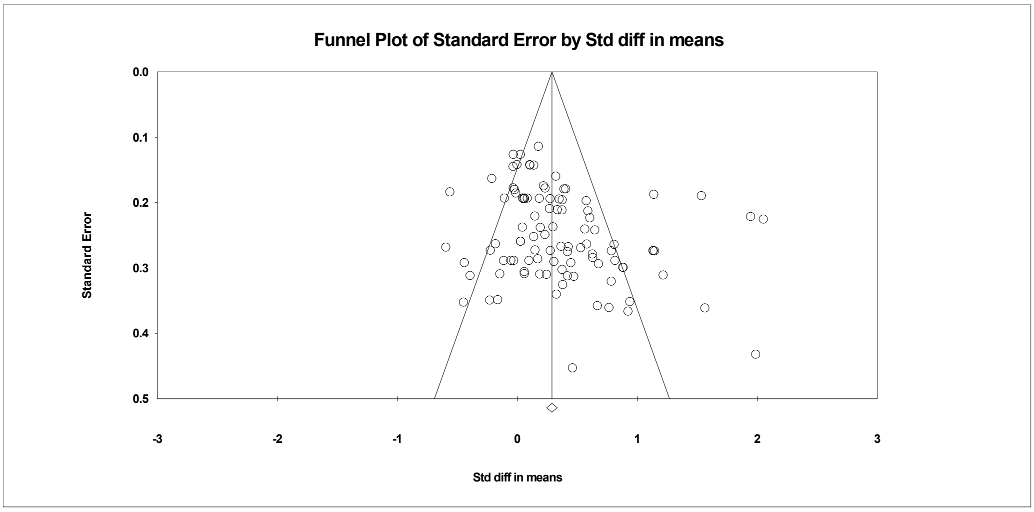

Figure 2 Funnel plot of publication bias test (including multiple experiments in the paper)

4. Results

4.1. Overall Effects of VDHPAs in VR Learning Environments

To investigate the impact of Virtual Digital Human Pedagogical Agents (VDHPAs) in VR learning environments on both learning processes and outcomes, five dimensions were analysed using a random-effects model: cognitive load, social presence, retention tests, transfer tests, and other tests. The main effects and heterogeneity statistics are reported in Table 4.

A total of 6 studies examined the impact of VDHPAs on cognitive load. Among these, 4 studies reported a reduction in learners' cognitive load, while 2 studies found an increase. The meta-analytic result showed a small and non-significant average effect size ($g = -0.084$), suggesting that VDHPAs in VR do not have a consistent influence on learners' perceived mental effort.

For social presence, 12 studies were included. Of these, 11 reported that VDHPAs significantly enhanced learners' sense of social connection in the VR environment. The pooled result yielded a statistically significant and moderate effect size (g = 0.402), with the 95% confidence interval (CI) entirely above zero.

Table 4. Main Effects of VDHPAs in VR Learning Environments on Learning Outcomes (Random Effects Model)

Outcome Variable	k	N	g	SE	95% CI
Process Variables					
Cognitive Load	6	834	–0.084	0.089	[–0.258, 0.090]
Social Presence	12	1832	0.402***	0.089	[0.228, 0.577]
Outcome Variables					
Retention Test	20	3746	0.451***	0.091	[0.272, 0.063]
Transfer Test	16	2271	0.288***	0.09	[0.111, 0.466]
Other Assessments	7	631	0.423***	0.129	[0.169, 0.676]

*Note: In meta-analysis, I^2 values of approximately 25%, 50%, and 75% are generally considered to represent low, moderate, and high heterogeneity, respectively.

Regarding retention, 20 studies reported relevant data. Among them, 15 indicated that VDHPAs supported learners in maintaining knowledge over time. The average effect size was moderate and significant (g = 0.451), and the 95% CI did not include zero, indicating a robust positive effect.

For transfer tests, 16 studies were included. Twelve of these studies showed that VDHPAs contributed to learners' ability to apply knowledge in new contexts. The resulting effect size was small but statistically significant (g = 0.288), and the 95% CI was entirely above zero.

Finally, 7 studies focused on other types of assessment, such as engagement or comprehension scores. 6 of these reported positive impacts of VDHPAs. The pooled result showed a moderate and significant effect size (g = 0.423), further confirming their beneficial role in improving learning performance across various indicators.

4.2. Heterogeneity Analysis

This study conducted heterogeneity tests for each of the five outcome variables, including cognitive load, social presence, retention, transfer, and other assessments (refer to Table 5). The results showed that all Q-tests were statistically significant, indicating substantial heterogeneity in effect sizes across studies.

For cognitive load and social presence, the I^2 values were 31.75% and 69.68%, respectively. This means that 31.75% and 69.68% of the total variation in effect sizes for these variables can be attributed to true heterogeneity rather than sampling error.

For the retention, transfer, and other assessments, the I^2 values were 81.37%, 76.27%, and 56.69%, respectively, indicating that a large proportion of the variance in effect sizes was due to real differences across studies.

According to Higgins et al. (2003), I^2 values of approximately 25%, 50%, and 75% are typically interpreted as representing low, moderate, and high heterogeneity. Based on this guideline, all five outcome variables in the present study exhibited moderate to high levels of heterogeneity, suggesting that the variability in effect sizes is non-negligible. Therefore, it is appropriate to apply a random-effects model for the analysis.

Moreover, the presence of such heterogeneity implies that the effects of VDHPAs in VR learning environments may be influenced by potential moderator variables. Accordingly, further moderator analyses were conducted to explore these effects.

Table 5. Heterogeneity Analysis Of VDHPAs In VR Learning

Outcome Variable	Q	df(Q)	p	I^2 (%)	Tau^2	SE	Variance	Tau
Cognitive Load	13.187	9	>0.05	31.749	0.024	0.036	0.001	0.154
Social Presence	62.657	19	<0.001	69.676	0.103	0.051	0.003	0.322
Retention	182.495	34	<0.001	81.369	0.229	0.077	0.006	0.478
Transfer	109.572	26	<0.01	76.271	0.158	0.064	0.004	0.398
Other Tests	16.161	7	<0.05	56.687	0.071	0.07	0.005	0.267
Cognitive Load	13.187	9	>0.05	31.749	0.024	0.036	0.001	0.154

*Note: In meta-analysis, I^2 values of approximately 25%, 50%, and 75% are generally interpreted as indicating low, moderate, and high levels of heterogeneity, respectively.

4.3. Moderating Factors Influencing the Effectiveness of VDHPAs

The inconsistent findings regarding the effectiveness of Virtual Digital Human Pedagogical Agents (VDHPAs) suggest the presence of potential moderating variables. Based on a review of existing studies, these factors can be categorised into three main domains: agent-related characteristics, learner characteristics, and instructional content features.

4.3.1. Agent-Related Characteristics

The design of the agent's appearance has a significant impact on learners' perception of social presence. Visual cues are particularly salient during the initial phase of interaction, when learners often have limited prior information and rely on visual impressions to judge the credibility of the agent. According to social cognitive theory, people tend to imitate and learn from models who resemble themselves. Hence, when a VDHPAs' appearance closely resembles a human, learners are more likely to find the agent relatable and credible. However, whether human-like avatars are consistently more effective than anthropomorphic ones remains debatable.

Gestures serve as a crucial form of non-verbal social cue. Research in both traditional and VR learning environments shows that when pedagogical agents use gestures during instruction, learners exhibit improved performance. Therefore, gestural expression is likely an important factor influencing the instructional effectiveness of VDHPAs.

Facial expressions also function as key social signals. Even subtle facial variations may significantly influence learners' perception of the agent's trustworthiness. In some cases, the perceived attractiveness of an agent's face may even outweigh considerations of reliability in determining its effectiveness.

Voice type is another influential factor. According to the voice principle in multimedia learning, human-recorded voices are more effective than computer-synthesised ones. Human voices possess unique prosodic features such as intonation and rhythm, which help convey social cues and stimulate emotional engagement. In contrast, synthesised voices often lack these affective qualities. Thus, human voice may enhance the social and instructional effectiveness of VDHPAs.

4.3.2. Learner Characteristics

Learning pace is a well-documented moderator in multimedia learning. It is typically classified into system-paced (externally controlled, such as in group settings) and learner-paced (self-regulated). According to the interactivity principle, learner-paced instruction can reduce cognitive load and improve performance by allowing learners to control the pace and sequence of information. However, the role of pace in moderating VDHPAs' effectiveness remains unclear. Some studies suggest that agents may not always be beneficial under learner-paced conditions, while others have found that VDHPAs are most effective when learners have control over instructional materials.

Learners' educational level may also moderate the impact of VDHPAs. These agents can spark learner interest, reduce negative emotional states, and offer instructional scaffolding to lower cognitive load. Nevertheless, few studies have systematically investigated how educational level affects agent-based learning. Age-related differences, in particular, warrant further examination.

Prior knowledge is a critical factor in multimedia learning. Learners with high levels of prior knowledge may experience the expertise reversal effect, wherein instructional strategies effective for novices become less effective—or even detrimental—for advanced learners. VDHPAs may be more helpful for novices by guiding their attention to relevant information, filtering out irrelevant stimuli, and reducing cognitive load.

4.3.3. Instructional Content Features

The subject domain may also influence the effectiveness of VDHPAs in VR learning. Existing empirical studies have predominantly focused on non-practical domains such as science, mathematics, and second language acquisition. Far fewer studies have examined practical subjects, and even fewer have demonstrated clear benefits for learning procedural or hands-on content using VDHPAs.

Some researchers have speculated that VDHPAs may be more effective for non-practical knowledge than for practical tasks. However, few experimental studies have directly compared learning outcomes across different content types. This gap in the literature may be due to challenges in designing learning materials and assessments that are equivalent in difficulty across disciplines. Thus, content type remains a potentially important moderator that requires further empirical validation.

In terms of knowledge type, declarative knowledge refers to facts and information that can be stated explicitly, while procedural knowledge involves knowing how to perform tasks, including cognitive strategies and motor skills. VDHPAs in VR may assist learners particularly in acquiring novel procedural knowledge, but their differential impact on declarative vs. procedural learning is still underexplored and warrants further investigation.

5. Discussion

This review synthesised findings from 47 effect sizes extracted from 36 empirical studies that evaluated the use of Virtual Digital Human Pedagogical Agents (VDHPAs) in Virtual Reality (VR) learning environments. The aim of this meta-analysis was to examine the agent-related characteristics, learner features, and experimental design conditions under which VDHPAs influence learning processes and outcomes.

5.1. Design Features of VDHPAs and Their Impact on Learning

Most studies preferred using 3D human-like avatars rather than other anthropomorphic designs, possibly because many VDHPAs were developed based on Social Agency Theory. According to this theory, the relationship between learners and the VR learning environment is treated as a form of social interaction. Thus, employing visual and verbal social cues—similar to those used in human communication—can enhance the learning experience. Human-like avatars are familiar to learners and capable of multimodal interaction, including speech, facial expressions, and gestures.

Although advances in computer graphics and modern modelling software since 2013 have enabled the development of realistic avatars, most pedagogical agents in education remain less sophisticated than those used in the gaming industry. Compared with cutting-edge virtual human agents, a key question remains: How does the lack of naturalness in instructional avatars affect cognitive and emotional outcomes in learners?

Despite technological progress, few studies have evaluated the instructional effects of VDHPAs within immersive VR. Yet immersive VR has been widely applied in higher education. In such contexts, well-designed VDHPAs can enhance the learning experience by creating presence and strengthening the learner-agent relationship.

All studies employing synthetic voices used commercially available text-to-speech systems. However, it remains unclear whether the quality of synthetic voice affects agent effectiveness. Few studies have examined this using metrics such as mean opinion scores.

The majority of VDHPAs were assigned a tutor role, offering instructional guidance and content delivery. This means that most agents were evaluated as knowledgeable entities providing domain expertise. A few studies compared different appearances or voices to explore distinctions between tutor, peer, or age-based roles. Almost all agents featured fictional identities; only one study modelled a real human character but paired it with mismatched synthetic speech.

Overall, studies suggest that agents with more human-like features tend to perform better. Yet few have evaluated the degree of anthropomorphism. Learners generally did not perceive the agents as highly human-like, and little improvement has been seen in recent VDHPAs. Future studies should consider learners′ perceived anthropomorphism as a factor influencing agent effectiveness.

5.2. Experimental Design Features and Their Impact on Learning

One notable finding is that very few studies evaluated VDHPAs with K−12 learners. Most research focused on university-level adults. This lack of representation means the current findings may not generalise to younger populations. Prior studies have shown that educational technologies may have stronger effects for K−12 learners, who have sometimes outperformed adult learners when interacting with VDHPAs.

Small sample sizes may also influence result reliability. Previous research has shown that studies with fewer than 250 participants may report effect sizes two to three times larger than those with larger samples. In this review, 33 studies (92%) involved samples of 250 or fewer, and only a few explicitly reported minimum sample size calculations.

Moreover, most studies were conducted in formal educational settings and within low-immersion environments. While VDHPAs have shown high effect sizes in non-VR K−12 contexts, it remains difficult to estimate their potential in high-immersion VR environments. Given recent advances in computer graphics, VR, and machine learning, the immersive and interactive nature of these technologies may differentiate them from earlier digital learning tools.

5.3. Learning Processes, Outcomes, and VDHPA Evaluation

Although most VDHPA studies focused on learning outcomes, learning processes such as cognitive load and social presence should also be evaluated. These processes influence not only what learners acquire, but how they learn. Factors such as learners′ expectations, instructional design variables, and post-learning reflection can all impact cognitive load and social presence throughout the learning cycle.

Because many process variables depend on learner perception, it is important to measure them directly. Yet in this review, only a few studies assessed learners′ perceptions of the agent. Among these, some reported negative feedback—such as robotic synthetic voices—which may suggest broader dissatisfaction. Without these evaluations, outcome data may unknowingly reflect learners′ negative perceptions of the agent itself.

Findings also indicate that the long-term effects of VDHPAs remain unclear. Most studies employed pre-tests and immediate post-tests. Only a few used delayed post-tests (one or two weeks later) to evaluate retention over time. While short-term recall provides some insight into learning effectiveness, long-term outcomes are equally important.

For instance, Govindasamy (2013) found no significant differences between conditions on immediate retention, but observed significantly higher delayed retention scores in the VDHPA condition one week later. This may be because the combination of visual and auditory cues enhances working memory and short-term recall. However, studies by Ahmadi et al. (2017), Li et al. (2019), and Tai et al. (2020) showed similar results for both immediate and delayed post-tests. Because most studies used only immediate post-tests, it remains unclear whether discrepancies between short- and long-term outcomes represent exceptions or general trends.

In terms of assessment format, multiple-choice questions (MCQs) were the most commonly used to evaluate lower levels of knowledge. Well-designed MCQs can assess factual recall and learning performance, and they support automated scoring and real-time feedback. However, while MCQs are suited for surface-level understanding, open-ended questions may be necessary to assess higher-order knowledge (Ozuru, Briner, Kurby, & McNamara, 2013).

6. Conclusions

This review systematically examined empirical research on VDHPAs in VR learning environments since 2013 through both narrative synthesis and meta-analysis. The study investigated agent-related features, learning environment characteristics, learner traits, experimental design, learning process measures, learning outcomes, and learner perceptions of agents.

The results suggest that the instructional potential of VDHPAs in VR environments has yet to be fully realised. Many of the reviewed studies demonstrated limitations in technology application, such as underdeveloped 3D modelling, rigid facial expressions and gestures, and limited immersion. Most VDHPAs adopted fictional identities rather than authentic representations.

Regarding learner demographics, K−12 populations were underrepresented in the current body of research, which limits the generalisability of findings across educational levels. Moreover, many studies had small sample sizes, reducing statistical power. In terms of interaction design, low-immersion VR environments may contribute to reduced learner engagement and social presence.

Although VDHPAs have demonstrated short-term benefits for learning outcomes, their long-term effects remain largely unexplored. Additionally, few studies have assessed learner motivation or perceptions of the agent, both of which are important for understanding how agents influence learning.

This review has several limitations. First, because meta-analyses require rigorous experimental controls, studies lacking control groups could not be included. This reduced the number of eligible studies and weakened the statistical power. Second, this review treated both human instructors and non-agent online learning as control conditions, potentially leading to an implicit ranking: human teacher > VDHPA > no agent. Future studies may consider separating these groups for more granular comparisons. Third, variables such as agent role or gender were not analysed quantitatively. Future meta-analyses should explore these additional features to determine their differential impact on learning outcomes.

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