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Exploring the Relationship between Brain-Based Learning and Thinking Skills through Smart Education: A Scoping Review on the Development of Study Material and Its Effectiveness

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Abstract. This scoping review examines the relationship between Brain-based Learning (BBL) and thinking skills in the context of smart education. The success of technological advancements in smart education depends on well-structured pedagogical approaches. The research investigates how BBL based on cognitive and neuroscience knowledge helps develop thinking skills in smart education. This review combines 36 studies from 2013 to 2023 through the Technology-Enhanced Learning of Thinking Skills (TELoTS) and smart pedagogy frameworks. The research shows that BBL enables students to develop higher-order thinking skills (HOTS) through learner-centred approaches that include problem-solving, critical thinking, and metacognition. The implementation of BBL faces ongoing difficulties related to curriculum development, assessment consistency, and expert participation. The study demonstrates how BBL strengthens smart pedagogy through its combination of cognitive principles with technology-based instruction which produces a learner-centered and educationally sound teaching model. Standardized assessments and interdisciplinary collaboration are recommended to maximize BBL's benefits in smart education.

Keywords: BBL, Thinking Skills, smart pedagogy, smart learning environments, smart education

1 Introduction

Brain-based Learning (BBL) focuses on principles and strategies that align with natural brain functions [47]. The core objective of BBL is to leverage neuroscience insights to enhance education by optimizing brain function and fostering a creative learning environment [96]. By linking BBL principles [13] with the brain's core networks, these networks collaborate to facilitate essential cognitive functions, thereby improving educational outcomes [10, 36, 43]. BBL research on brain-based optimal education which is built upon knowledge, character and wisdom [96], aligns with smart education research, which addresses the methodological aspects of smart

pedagogies and smart learning environments (SLEs) to nurture smart learners [13, 49, 108]. A smart learner encompasses both wisdom and intelligence, enabling quick and clever thinking with sound judgments and problem-solving skills that are relevant across diverse cultural contexts in various situations [108].

Comparing BBL to other cognitive and constructivist learning models requires an examination of its key pedagogical and neurological aspects. BBL draws its foundation from neuroscience to support instructional methods which match the brain's natural learning processes [13, 49]. Cognitive learning models focus on learning mechanisms that involve information processing and working memory, emphasizing structured learning environments and sequential scaffolding to improve retention [57]. BBL differs from traditional learning models. It operates through ongoing, dynamic processes that continually evolve. The learning mechanisms operate in a fixed linear manner until activation, but BBL exists in a perpetual state of transformation because they interact reciprocally with their environments. The ongoing transformation becomes visible in BBL's responses to changing conditions because their components exist in continuous flux which affects and gets affected by the entire system [66, 71]. The constructivist approach to inquiry-based learning places student-centred exploration at its core, as students create new knowledge through connections to their existing knowledge base [104]. Both BBL and constructivism promote active, engaged learning. BBL stands out because it incorporates findings from neuroscience on how emotions and sensory inputs influence memory retention [13, 54]. The comparison shows that constructivism focuses on student knowledge development, but BBL enhances this process through neuroscience-based optimisation of experience structure and internalisation [13, 49, 85]. The comparison demonstrates BBL's ability to unite brain science with teaching methods which tackle both mental and emotional aspects of learning.

Cognitive and emotional domains converge in thinking skills, which involve analyzing and evaluating information from experiences and observations [7,102]. The literature on thinking skills covers a broad spectrum of cognitive processes. These skills include key components such as reasoning, creative and reflective thinking, critical thinking, problem-solving, and argumentation [12], which are essential for cognitive growth and widely applicable in educational and professional settings. The Applied Thinking Skills (APTS) framework defines six fundamental skills: comparing and contrasting, classification and grouping, recognizing reasons and conclusions, idea generation, decision-making, and problem-solving [11]. It emphasizes practical approaches that enable learners to structure and evaluate information more efficiently. Bloom taxonomy classifies thinking skills into lower-order thinking skills (LOTS) and Higher-order thinking skills (HOTS) [2,73]. HOTS are essential for developing a 21st-century generation capable of global competitiveness, fostering intelligence, creativity, and innovation [105]. A systematic review highlights that incorporating Higher Order Thinking Skills (HOTS) into science education provides valuable insights for educators and policymakers, guiding the development of more effective curricula and learning strategies to prepare students for an increasingly complex and technology-driven future [23]. The goal of smart education is to develop a workforce equipped with 21st-century knowledge and these thinking skills to address societal challenges [108].

The smart education framework comprises three key components: smart environments, smart pedagogy, and smart learners, all designed to enhance educational quality. It emphasizes that effective pedagogy and technology-rich environments work together to support the development of learners who are adaptive, engaged, and capable of independent thinking [108]. There are gaps in the existing literature on smart education that often prioritizes technological innovations over pedagogical strategies [26, 70], despite evidence [46] that both elements must be balanced to achieve an effective, human-centric instructional design [67, 108]. Research in smart learning environments (SLEs) suggests that while technological advancements are pivotal, their effectiveness is largely determined by the underlying pedagogical strategies [108]. BBL research focuses on creating an optimal learning environment and model that wisely integrates technology, forming a solid foundation for smart pedagogy [13, 51, 87, 95, 97, 108], it plays a crucial role in guiding ethical decision-making within artificial intelligence (AI)-enhanced educational systems [31]. Numerous researchers have highlighted the challenges of applying neuroscience findings to classroom settings, emphasizing the need for additional research and practical experimentation in real educational contexts. To tackle this issue, they have condensed various neuroscientific insights into key principles within the framework of optimal learning stages [14, 49]. These principles enhance educators' understanding of the learning process, enabling more informed curriculum design and instructional decision-making [56, 74, 86].

Previous systematic reviews and meta-analyses have investigated BBL's theoretical foundations and pedagogical aspects, as well as its learning effects; however, few studies have examined its application in instructional design for the development of thinking skills [5, 6, 27, 35, 37, 69]. The context-dependent nature of smart education effectiveness requires a structured analysis of BBL's role in developing thinking skills within smart education frameworks [67, 70, 97, 108]. The evaluation of thinking skills requires essential research on assessment tools, strategies, and instruments, as well as curriculum design, learning strategies, and educational technology research that enhance cognitive processes. Systematic reviews and meta-analyses have evaluated the effectiveness of BBL; however, an exploratory review is needed to identify research gaps and inform the development of pedagogy and evidence-based educational policies.

The scoping review investigates BBL thinking skills through the use of Technology-Enhanced Learning of Thinking Skills (TELoTS) [70] and smart pedagogy framework [67] as base references. The pedagogical framework guides the development of smart learning environments, which focus on developing thinking skills [70]. The smart pedagogy framework provides recommendations for curriculum design and strategies for implementing intelligent tutoring systems to improve higher-order thinking skills [67]. The TELoTS framework and Smart Pedagogy framework differ from traditional educational technology frameworks and generic technology integration models because they focus on structured pedagogical approaches rather than digital tools, content delivery, and automation. These frameworks direct instructional design to thinking skills development to create learning experiences that extend past technological integration. Through strategic learning activity orchestration and scaffolding they enhance BBL application in smart learning

environments to promote deeper cognitive engagement and skill development. These frameworks have strong justification for inclusion.

This review examines applied principles, curriculum design methodologies, learning strategies, and educational technologies, as well as assessment tools, strategies, and instruments used to evaluate thinking skills. The review's primary goal is to synthesize existing evidence on these topics and identify gaps that can inform the advancement of smart pedagogy and policy-driven educational strategies, ensuring that the integration of technology and pedagogy fosters meaningful and effective learning experiences. By providing a structured and in-depth exploration that extends beyond previous studies, this scoping review offers fresh insights into optimizing instructional design for 21st-century learners.

2 Methodology

Methodological frameworks proposed by Levec et al [58] and a checklist from PRISMA Extension for Scoping Reviews (PRISMA-ScR) [99] were used to conduct the scoping review. We developed and registered the review protocol under the Open Science Framework [103]. A streamlined approach to rapid scoping review was used, with necessary minor changes made during the review process due to time constraints and resource limitations. These changes included having a single reviewer conduct the entire literature retrieval and screening process under supervision, limiting searches to the most relevant databases, not contacting study authors for missing information, and restricting the extent of analysis [8, 43].

We used 5 electronic databases—Ovid MEDLINE, Embase, Scopus, CINAHL and Web of Science to apply the same set of keywords with Boolean operators ("brain based learning" OR "brain based teaching" OR " brain based learning strateg* " OR "neuropedagogy" OR "brain based" AND "higher order thinking skills" OR "Bloom's Taxonomy" OR "critical thinking" OR "skill") to locate the relevant articles. A standardized set of search terms was consistently applied across databases, with minor adjustments, such as MeSH or Subject Heading field searches, tailored to each platform's requirements. We refined our search strategy based on expert recommendations, as part of our search validation procedure. The reviewer was guided and consulted by the university librarian to refine the search strategies, including trying out and selecting suitable databases using the correct steps. We also refined our search strategy based on existing literature. One crucial adjustment was made based on a systematic review by Liu et al [61] to replace 'thinking skill' with 'skill' in our search terms, recognizing it as the second most frequently used keyword after 'critical thinking' in research on thinking skills. This change broadened our scope to collect relevant but potentially reduces specificity.

The inclusion and exclusion criteria for this review were developed using a combination of the PICOS (Population, Intervention, Comparison, Outcome, Study Design) and SPIDER (Sample, Phenomenon of Interest, Design, Evaluation, Research type) frameworks [19] to ensure a focus on relevant and high-quality studies addressing the relationship between BBL and thinking skills. The inclusion criteria, based on the systematic reviews mentioned in the introduction section, are as follows:

studies that focus on learners of any age group (children, adolescents, or adults) in formal educational settings, including primary, secondary, and post-secondary education (Population/Sample). Additionally, studies that explicitly examine BBL strategies, such as the use of multisensory instruction and priming, as interventions (Intervention/Phenomenon of Interest) were included. The review focused on studies that measure or assess thinking skills as an outcome, using instruments and experimental designs to track changes in cognitive skills (Outcome/Evaluation). The inclusion criteria extended empirical studies, including quantitative, qualitative, or mixed methods designs, as well as randomized controlled trials (RCTs) and quasi-experimental studies (Study Design). Research types considered for inclusion included peer-reviewed journal articles, conference proceedings, and dissertations (Research Type). The studies had to have been published within the last 10 years (2013–2023) and in the English language. We also changed the timeframe to include only articles published between 2013 and 2023 instead of 2014 to 2024, as the search was initiated before the end of 2024, and some of the selected databases did not allow limiting the timeframe by month but only by year.

The selection of a 10-year publication window for this scoping review was based on the notable advancements in neuro-pedagogy and neuroscience-driven educational research within the past decade. While research in this field has existed for several decades, earlier studies often relied on unrefined or unvalidated methodologies. In contrast, recent years have witnessed significant developments in neuroimaging techniques, accompanied by the integration of emerging technologies, such as virtual reality. These advancements have provided more robust, data-driven insights into BBL. Given the focus on neuroscience and neuro-pedagogy, prioritizing recent literature ensures that this review captures high-quality, validated research that reflects the most current technological and theoretical progress in the field.

The exclusion criteria for this review were as follows: studies that did not focus on the application or effects of BBL or thinking skills development were excluded, as were those primarily addressing clinical populations (e.g., individuals with neurological disorders or psychological conditions) without direct relevance to learning or thinking skills in educational settings. Studies emphasizing technology, such as apps or software, that did not directly assess their impact on BBL, or cognitive skill development were also excluded. Additionally, studies focusing on research methodologies, statistical tools, or measurement instruments unrelated to BBL were not considered. Neuroscientific research that lacked a clear connection to educational contexts, learning strategies, or thinking skills was excluded, along with meta-analyses, systematic reviews, or literature reviews that did not present new empirical data. Duplicate studies and those for which the full text was unavailable were also excluded from consideration.

The screening process for the articles involved multiple phases, as shown in Figure 1, guided by the established inclusion and exclusion criteria. Initially, a doctoral student conducted the literature search as the primary screener. Duplicate records were removed using Zotero, followed by a manual review of titles and abstracts of 636 articles. The screener was able to view only the title, abstract, author, and publication year of each article, while journal names and country of origin were concealed to reduce bias and maintain an objective evaluation. The primary focus was on determining whether the articles met the eligibility criteria based on their titles

and abstracts, with other bibliographic details consulted only when necessary for the eligibility assessment. In the second phase, the primary screener examined 131 full-text articles to evaluate their eligibility for inclusion. In the third phase, 36 articles were included after excluding 88 articles with documented exclusion reasons. The entire process of literature retrieval and screening was closely overseen by the main supervisor, who reviewed the outcomes. Any disagreements or uncertainties were resolved through discussion between the authors. Notably, the entire screening process was conducted manually, without the use of automation.

The screening identified 36 articles for synthesis, and data from both quantitative and qualitative studies were extracted and organized into two tables. The extracted information included metadata such as author(s), publication year, applied principles or cognitive theories, as well as details on the development of study materials, specifically the design and validation of BBL materials and instruments for measuring thinking skills to ensure data reliability. Additionally, information on participants (e.g., students, teachers, and other relevant groups) was gathered alongside the targeted measures and outcomes. The sample size (n) of each study was also recorded. Furthermore, this review extracted information on designed learning activities, including learning strategies and educational technologies used [67, 70] from the selected studies. The data extracted from the two tables in the registered protocol, along with details on the designed learning activities, were compiled into Tables 1, 2, and 3 to ensure that the information effectively captures the breadth of evidence in scoping reviews. Among the 36 included articles, 27 were empirical studies involving participants, as shown in Table 1 and Table 2 (Appendix A), while 9 studies did not involve any participants, as shown in Table 3 (Appendix A). In terms of categories of empirical studies, among the 27 empirical studies that involved participants, 21 studies, as shown in Table 1, were experimental, quasi-experimental, or mixed-methods studies. Meanwhile, another 6 studies, as shown in Table 2, were descriptive and involved surveys or interviews. Of the 9 studies that did not involve any participants, the majority were content analysis and observational studies, as shown in Table 3.

The characteristics of the tabulated studies were synthesized using a narrative synthesis approach, as documented in the registered protocol, to identify key themes and patterns observed across the included studies. The analysis was restricted [39, 66] to analyzing only the information on applied principles or cognitive theories, outcomes and thinking skills. Restricting the analysis facilitated a more efficient data extraction process while preserving the accuracy and reliability of the findings. Focusing specifically on these core areas allowed the analysis to remain aligned with the aim of this review, which is to examine the relationship between BBL and thinking skills without being diluted by excessive thematic complexity. Additionally, this focused approach ensured that the analysis stayed directly relevant to the study's goal, preventing diversion into broader aspects of study material development, which could be more effectively explored using narrative synthesis.

Thematic content analysis was conducted, allowing for the synthesis of all data into overarching themes while transforming textual information into meaningful codes, themes, and categories. This approach aligns with systematic review methodologies used to examine the effects of gamification as a pedagogical tool in learning and instruction [107], as well as a BBL research in adult education and human resource

development [45]. Thematic analysis was employed to identify and interpret recurring patterns of meaning within qualitative data [9], while content analysis was employed due to its applicability to both qualitative and quantitative data [45, 55].

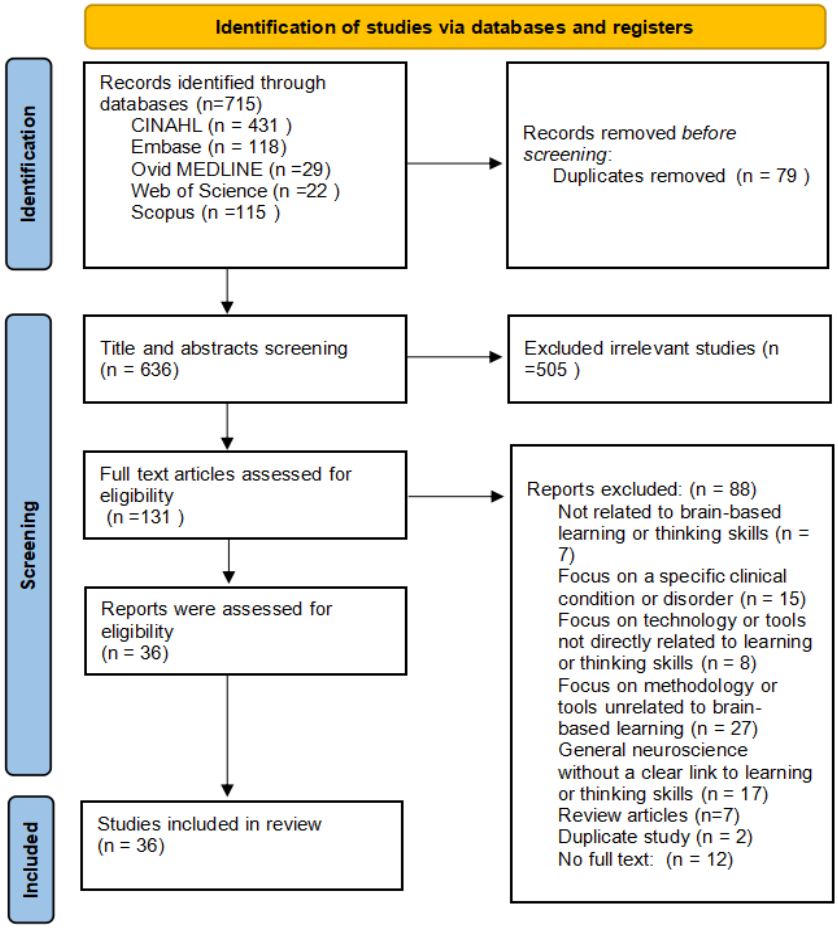

Fig. 1. The review screening process for the articles

3 Results

3.1 Characteristics of the Tabulated Studies

Participants. Among the 27 empirical studies, 19 involved students as participants, 4 involved educators (teachers, higher education instructors, and academics), and 3 involved medical professional staff.

Principles/Cognitive Theory. Sixteen studies from the 36 empirical studies applied similar brain-based learning principles proposed by specific authors, such as Jensen [48] and Caine [13–15]. Of these, 4 studies utilized Caine's 12 principles, 4 adopted Caine's 12 principles plus 3 foundational elements, and 1 combined Caine's principles with other approaches, including brain-compatible and brain-friendly learning. Additionally, two studies used Jensen's principles, two incorporated both Jensen's and Caine's approaches, and one combined the approaches of Jensen, Caine, and Brain Gym. Another 2 studies employed a 4-phase brain-based lesson plan for simulation, focusing on inquiry, gathering, processing, and application. Most of the studies (n = 20) applied principles from cognitive theories, often tailored to specific professional fields. For instance, 6 BBL principles were employed in the context of design and visual arts education. Additionally, BBL models focusing on knowledge representation, clinical decision-making, and EEG characteristics were utilized in clinical decision-making contexts. The embodied cognition approach, particularly the Mirror Neuron System, was applied within aviation training.

Development of BBL Materials. Among the 36 empirical studies, 30 studies reported about the development process of BBL materials. Many of the studies (n = 23) designed their BBL materials based on the literature, without involving external parties other than the research team. One study consulted an expert during the development phase, while three studies developed BBL materials and subsequently validated them with input from field experts. Additionally, 1 study employed the 4D model—comprising the stages of defining, designing, developing, and disseminating—during the material development process. Two studies utilized either Plomp's methodology or a modified version of the 4D model (limited to defining, designing, and developing), involving experts for material validation.

Learning Activities. Of the 36 empirical studies, 25 reported on learning activities used in BBL materials, with most studies incorporating multiple types of activities. Among these, videos, animations, or cinema were the most frequently used, appearing in 8 studies, as were role-play and group work, also found in 8 studies. Hands-on activities appeared in 6 studies. Images and quizzes were used in four studies each. Concept maps and physical activities were incorporated in 2 studies each, and having meals before or during class was also reported in 2 studies. Feedback was noted as an activity in 2 studies. Less common activities included slides, games, working memory training, and seminars, each of which appeared in only one study.

Development of Measuring Instruments. Of the 36 empirical studies, 27 provided information on the development process of BBL measuring instruments, but only 8 addressed the validity and/or reliability of the instruments used. Of these, 3 studies validated all instruments through expert consultation or specialization and conducted pilot testing. One study validated all instruments solely through expert review, while another 2 studies reported validation for only half of the instruments. Additionally, two studies focused on the reliability of the instruments, and one used a specific, validated test instrument. Most of the studies (n = 20) used assessments designed by educators based on the tested subject or by the instrument researcher based on the

literature, without reporting the validity and reliability of the instruments used. Of these, one study modified the instruments based on existing assessment rubrics, such as the Cambridge Speaking Assessment Rubrics, and another study used modified instruments based on Bloom's Taxonomy.

Thinking Skills. Among the 36 empirical studies, 30 specifically evaluated thinking skills as outlined in the introduction. The breakdown of assessed skills was as follows: reasoning in 8 studies, argumentation in 2, and retention, course knowledge, and didactic knowledge in 4. Problem-solving was evaluated in two studies: decision-making in one, critical thinking in five, and creative thinking in one. Reflective thinking was examined in 2 studies, and metacognition was explored in 1. Additionally, lower-order thinking skills (LOTS: knowledge, comprehension, and application) were assessed in 1 study, while general higher-order thinking skills (HOTS) were evaluated in 1 study. Another 10 studies evaluated skills related to thinking such as literacy skills, mathematical skills and executive function. Several studies (n=6) showed that thinking skills were not directly measured as outcomes but were incorporated into the BBL framework through the instructional design.

Effectiveness of BBL Strategies in Enhancing Different Types of Thinking Skills. Among the 36 studies, 31 reported that BBL positively influenced thinking skills, with 1 study showing that BBL affected cognitive, affective, and metacognitive aspects but had no significant impact on critical thinking. Educators from 4 studies acknowledged the role of BBL in enhancing thinking skills, but two of the studies also mentioned difficulties in implementing BBL. The studies varied in sample size, ranging from small groups (n = 5) to larger groups (n = 512). This variation could impact the generalisability of the findings.

3.2 Thematic Content Analysis Results

Based on the identified frequently used phrases from information on principles, cognitive theories, outcomes, and thinking skills, five themes emerged and are summarised as shown in Table 4 and Table 5.

Table 4. Thematic analyses: BBL

Frequently Used Phrases: Principles/Cognitive Theories	BBL Themes
"12 BBL principles" , "3 BBL foundational elements", "7 stages of brain-based planning"	BBL Frameworks
"model", "4-phase brain-based lesson plan", "framework"	Instructional models
"cognitive", "EEG"	Cognitive Mechanisms

Table 5. Thematic analyses: Thinking skill outcome

Frequently Used Phrases: Outcomes And Thinking Skills	Thinking Skill Outcome Themes
"significantly higher", "significantly improve", "significant", "control group"	Comparative Performance Analysis
"not reported"	Non-Comparative Performance Analysis

Table 6. BBL principles organized in relation to components of the smart pedagogy framework

	BBL Principles/ Cognitive theory		
Thinking skill outcomes	BBL Frameworks	Instructional Models	Cognitive Mechanisms
Comparative Performance Analysis	12	5	3
Non-Comparative Performance Analysis	7	4	5

Based on the emerging themes for BBL across all 36 studies, 19 studies fall under the "BBL Frameworks" category, nine studies fall under the "Instructional Models" category, and eight studies fall under the "Cognitive Mechanisms" category. Regarding the themes related to thinking skills outcomes across all analyzed studies, 20 studies fall under "Comparative Performance Analysis", while 16 studies fall

under "Non-Comparative Performance Analysis." These themes have been converted into a co-occurrence matrix to visualise the relationship between BBL themes and thinking skills outcome themes using a heatmap, as shown in Table 6. The values represent the frequency with which each BBL theme is associated with a thinking skills outcome theme.

4 Discussion

This scoping review explored the relationship between BBL and thinking skills through a systematic synthesis of 36 studies. Although not a formal meta-analysis, our thematic aggregation and frequency-based synthesis provide a meta-analytic orientation that yields several effective insights and methodological reflections. Both the TELoTS framework [70] and the smart pedagogy framework [67] serve as foundational references, in designing SLEs [67, 70] and the pedagogical contexts within them. Researchers analyzed these through a Technology-Enhanced Learning perspective [95]. In this paper, BBL studies emphasizing the cultivation of thinking skills are reviewed. The findings indicate that almost half of the studies applied cognitive theories tailored to specific professional fields, while 44% (16/36) of the studies incorporated BBL principles introduced by BBL experts such as Caine [13] and Jensen [49]. Findings from educational neuroscience research have motivated educators to develop Brain-Based Learning (BBL) approaches [79]. These experts in BBL provide frameworks that are both straightforward and grounded in an understanding of neuroscience [16, 45], which relate to the theme of BBL frameworks. Educators utilize these principles to select brain-aligned methods that foster active learning [27,28, 93]. Teachers then act as facilitators in this process [93]. Such student-centred learning design corresponds to student-centred pedagogical approaches that are widely supported in SLEs [89, 95]. BBL also supports SLEs by enabling the creation and integration of diverse learning resources with technologies, including documents and videos [21, 22, 59, 60, 76, 82, 90, 91, 100]. This result aligns with findings from a systematic review on the teacher's requirement to possess a well-integrated understanding of lesson content, diverse pedagogical methods, and the appropriate technological tools to enhance learning based on neuroscience [80].

The findings of this review, as presented in Table 1 and Table 3, indicate that BBL studies are organized around the main components of the smart pedagogy framework [67] as shown in Figure 2. Researchers used core principles or cognitive theories as key elements to shape curriculum design and guide the development of learning resources. As in Figue 2, teaching strategies encompass a range of learning activities that incorporate both educational methodologies and technological tools [55, 95]. Fifty six percent (20/36) of the studies applied different cognitive theories tailored to specific professional fields related to the theme of cognitive mechanisms. These studies designed BBL material and learning activities aligned with the chosen cognitive theories and study contexts.

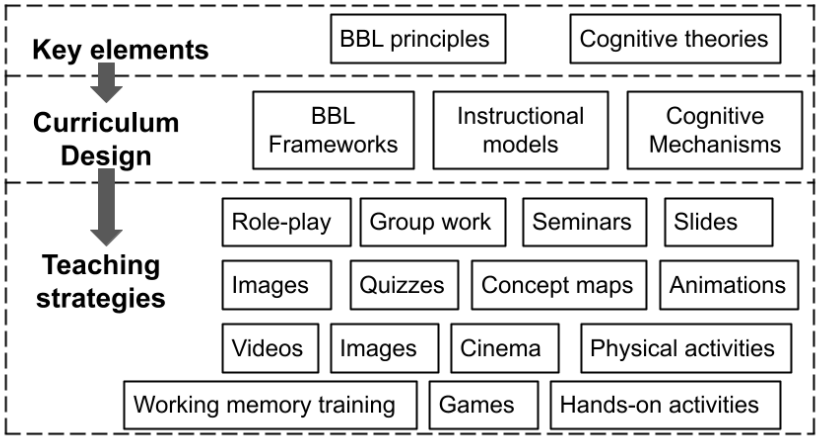

Fig. 2. BBL principles or cognitive theories as key elements to shape curriculum design and guide teaching strategies incorporating educational methodologies and technological tools

One study found that students who learned with a human-like pedagogical agent (PA), designed according to social agency theory and incorporating eye gaze and gestures into online multimedia lessons, achieved higher scores on learning outcome tests. Neurophysiological measures also indicated increased brain activity in regions associated with social processing during learning [59]. This underscores the potential of integrating such PA into AI-driven tutoring systems to enhance engagement and cognitive processing [54] within SLEs aligned with BBL. This can be applied in digital learning platforms by incorporating virtual guides that emulate human traits, such as expressive facial gestures and body language to enhance learner motivation and support metacognitive development. BBL contributes to smart pedagogy by informing the development of more human-centric, pedagogically sound smart education practices

A key takeaway is BBL's versatility and applicability in low-resource settings. Contrary to the perception that neuroscience-based methods are resource-intensive, this review reveals BBL can promote equity by providing cost-effective and flexible strategies. BBL, which encompasses methods such as multimodal instruction, sensory involvement, and emotional engagement, can be adapted to suit educational settings with limited resources. For instance, sensory-based activities such as role-playing, group work [4, 17, 18, 21, 35, 44, 75, 82], or incorporating movement into lessons [75, 83] do not rely on expensive technology but still effectively stimulate different areas of the brain to promote learning. Application in real classrooms can involve having teachers implement inquiry-driven collaborative projects where students explore real-world problems, co-create solutions, and communicate their findings through methods such as storytelling or classroom simulations. This strategy effectively engages students on an emotional level while also enhancing their critical thinking skills. Similarly, affordable tools such as free online videos [98] or the creation of visual learning materials [21, 59, 60, 76, 82, 90, 91, 100] can help create

immersive learning experiences without requiring advanced resources. The feasibility of BBL in these contexts is enhanced by its focus on active learning and emotional connection, which can be facilitated through simple, low-cost activities such as storytelling, collaborative tasks, or hands-on learning [17, 18, 27, 32, 65, 75] using everyday items. By emphasising these adaptable techniques, BBL remains an accessible and practical teaching approach, even in settings with financial limitations, supporting cognitive growth with minimal financial investment.

The results reveal that 77% (23/30) of the studies reporting on the development of BBL materials relied solely on literature-based design without external collaboration beyond the research team. While integrating insights from learning science literature is essential for aligning metacognitive processes with instructional strategies in smart learning environments (SLEs) [71], expert involvement in curriculum design remains crucial [48, 71]. This is particularly important for cognitive task analysis [71] and ensuring that contextual factors and technological integration are effectively considered in the implementation of smart education [46]. The results, as presented in Table 1 and Table 2, indicate that 74% (20/27) of the studies utilized assessments created either by educators based on the subject being tested or by instrument researchers drawing from existing literature. However, these studies did not report the validity or reliability of the assessment instruments used. The TELoTS framework suggests that literature analysis can be a useful method for identifying competencies, especially when previous research has already broken down a thinking skill into sub-skills and measurable competencies. However, it may not always provide a complete framework. In some cases, existing literature may only offer a partial understanding or fail to provide a comprehensive definition of certain thinking skills [70]. This gap reinforces a key takeaway from BBL research, which highlights the need for stronger methodological standardization in both curriculum and evaluation tools to ensure transferability and scalability.

Two meta-analyses on BBL emphasized the need for the standardized development and validation of instructional tools to reliably measure BBL's cognitive benefits across diverse educational contexts [35, 39]. These meta-analyses have produced mixed results regarding BBL's overall effectiveness. Funa's study reported a significant effect size (ES = 3.135), highlighting a strong positive impact of BBL on cognitive skills and conceptual understanding, particularly in STEM education [35]. In contrast, Gözüyeşil and Dikici found a more moderate effect size (d = 0.64) when evaluating academic achievement, suggesting that BBL's effectiveness depends on the specific outcomes assessed and the research methodologies used [41]. This scoping review aligns with Funa's findings, confirming BBL's potential to enhance thinking skills required for conceptual understanding and academic performance [35]. However, it also identifies inconsistencies in the validation of BBL materials. Differences in the application of BBL strategies, as well as variations in effect size calculation methods may contribute to these discrepancies. These findings underscore the importance of establishing standardized methods for developing and validating instructional materials to ensure the reliable measurement of BBL's cognitive benefits across different educational settings, echoing calls from meta-analysts for greater rigor in measuring study outcomes.

BBL has a positive influence on the cultivation of thinking skills according to the results. The most frequently measured thinking skill is reasoning. HOTS variables

such as the cognitive domain of Bloom's taxonomy, problem-solving, critical thinking, reflective thinking, metacognition and creative thinking [55,56] are also found in 9 studies among the reviewed studies [23, 27, 32, 34, 42, 60, 62, 76, 100]. This scoping review offers a comprehensive analysis of the connection between BBL and thinking skills, drawing insights from a range of empirical studies. Studies demonstrate that BBL strategies can have a direct impact on improving thinking skills [54, 56, 64], a finding that aligns with the conclusions of this review. At the same time, thinking skills can influence both the application and effectiveness of BBL strategies. In certain studies, thinking skills were not assessed as distinct variables but were embedded within the BBL framework as part of the instructional approach. This integration suggests that incorporating thinking skills into BBL enhances its overall effectiveness, fostering deeper cognitive engagement and leading to improved learning outcomes. These findings suggest that thinking skills are not merely a byproduct of BBL but rather play an active role in shaping the learning experience.

BBL offers an innovative educational paradigm that nurtures human potential for the evolving future [96], which can contribute to the goal of smart education in cultivating smart learners [108]. Integrating neuroscience with the enhancement of thinking skills presents a novel approach to the existing literature, particularly when investigated through innovative experimental methodologies and fresh theoretical perspectives. The distinctiveness of this approach lies in applying neuroscience to substantiate and refine these educational strategies [56, 75, 86]. Emerging neuroeducation research, including the utilization of neuroimaging technologies such as EEG and fNIRS [10, 36, 49, 55] to observe cognitive changes during BBL interventions [56], offers new insights into how brain activity is linked to the development of critical thinking, problem-solving, and creativity [52].

Integrating BBL into smart education requires a well-structured approach to interaction design, ensuring that learning environments are both engaging and effective. A study utilized brain imaging techniques to examine cognitive activity during the initial stages of design, emphasizing the importance of aligning design processes with cognitive functions [33]. This study aligns with one of the included studies on brain-based medical education, which analyzed EEG patterns to differentiate expert and novice clinical decision-making, ultimately guiding the development of BBL strategies for medical expertise [50]. The role of cognitive processes in clinical decision-making is like that of cognition and behaviour in optimizing interfaces and experiences in interaction design. Both fields leverage brain activity analysis to enhance learning, problem-solving, and expert performance. By adopting these interaction design strategies, educators can develop brain-compatible smart learning environments that support critical thinking and cognitive skill development.

Based on the review findings, a set of initial design guidelines can be proposed for educators and educational technology developers seeking to incorporate BBL into their instructional environments. Key considerations include structuring learning experiences around core BBL principles, such as fostering emotional connection, integrating multiple sensory modalities, and ensuring relevance to learners' contexts. Educators should also incorporate reflective tasks and encourage group-based problem-solving, while designing activities that align with learners' cognitive readiness and developmental progression. In digital learning contexts, embedding

features such as responsive, human-like virtual tutors and systems that provide tailored feedback can enhance learner engagement and facilitate deeper metacognitive processes. These principles offer a practical framework for designing effective, neuroscience-informed SLEs.

5 Limitations and Future Research Directions

While this review provides a comprehensive overview, it is essential to acknowledge its limitations, including potential publication bias and variability in the quality of the included studies. The included studies reveal several methodological flaws that could affect the overall conclusions of the review. One key weakness is the limited validation of the instruments used to evaluate the effectiveness of BBL strategies [18, 36, 60, 82, 81, 89]. Many studies employed custom-made tools without adequate testing for validity or reliability, which raises concerns about the accuracy of the findings. Another issue is the small sample sizes, which limit the generalisability of the results. Studies with restricted participant numbers, particularly those focused on specific educational contexts, may not capture the full scope of BBL's potential impact.

Additionally, inconsistencies in study designs, ranging from quasi-experimental methods to purely descriptive approaches, complicate the assessment of BBL's influence on thinking skills. Notably, the absence of control groups in several studies (Tables 2 and 3) makes it challenging to attribute any observed benefits to BBL interventions with confidence. These limitations underscore the need for more rigorous research methodologies, including larger and more diverse sample sizes, validated measurement tools, and carefully designed experiments, to provide stronger and more reliable evidence of BBL's effectiveness in fostering cognitive development. While the streamlined approach in this rapid scoping review may introduce certain biases, these pragmatic adjustments were deliberately chosen after thoroughly evaluating team expertise, literature scope, review objectives, synthesis methods, limitations, and intended audiences to maintain a balance between efficiency and methodological rigour under constraints of time and resources [8, 43]. This review methodology is becoming increasingly essential for evidence-informed decision-making in education, particularly in designing and conducting rapid evidence syntheses that prioritize transparency and replicability while upholding the essential methodological standards [100]. Future research should focus on longitudinal studies to assess the sustained impact of BBL strategies over time, as well as comparative studies to evaluate the effectiveness of different BBL models. Additionally, expanding the participant pool to include diverse educational settings and learner demographics could yield insights into the generalisability of findings.

6 Conclusion

This review underscores the potential of BBL to enhance thinking skills. However, it also reveals variability in outcomes depending on methodological choices and

contextual factors. To address this gap, policymakers and educators should incorporate neuroscience-based pedagogy into teacher education programmes, equipping instructors with a comprehensive understanding of the subject matter, a range of teaching strategies, and effective technological integration [20, 79, 80]. Moreover, establishing standardized frameworks for developing and validating BBL-driven instructional materials is crucial for enhancing the consistency and accuracy of cognitive assessments. Additionally, expanding equitable access to smart learning technologies will enable students from all socioeconomic backgrounds to benefit from BBL-enhanced education. By adopting these approaches, educational institutions can cultivate dynamic, technology-supported, student-centred learning environments [81] that support the broader objective of smart education in preparing learners for the complexities of a knowledge-driven world. Smart pedagogy, SLEs, and smart learners are three elements involved in smart education that can benefit from BBL, ultimately contributing to SLEs that enhance thinking skills and benefit smart learners, as illustrated in Figure 3.

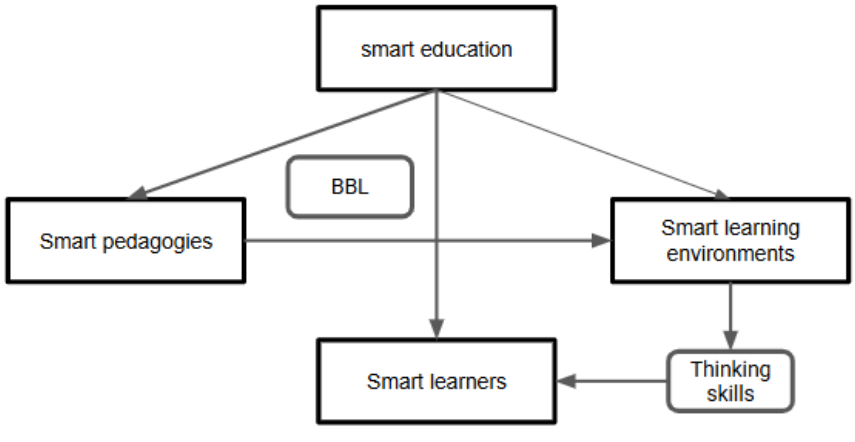

Fig. 3. Elements involved in smart education that can benefit from BBL

BBL establishes a structured foundation for smart pedagogy with a collection of innovative teaching strategies designed for smart learning environments [13, 54, 67, 97]. BBL can contribute to SLEs by highlighting the importance of creating a technology-driven learning environment that fosters effective learning while advocating for a wisdom-based educational approach to guide the use of technology [67, 95, 97]. Smart learners can benefit from BBL, which incorporates student-centred learning, to cultivate their thinking skills [67, 70, 97].

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Appendix A

Table 1. Characteristics of experimental, quasi-experimental, and mixed-methods studies involving participants

(A))/ Year	Ps/n	Principles/ Cognitive Theory	Development of BBL Materials	Learning Activities	Development of Measuring Instruments	Outcome
Rasheed et al. [81]/ 2023	students / 40	12 BBL principles plus 3 BBL foundational elements	Prior to the study, the female teacher underwent four hours of training to learn how to apply BBL strategies. The researcher provided instructions for implementing all activities and lessons.	-trained in role-playing, inquiry, listening, and initiating calmness, with positive reinforcement for their responses. -showing children colourful images to describe and engaging them in sensory information gathering, tool organization -recognize positive and negative behaviours through illustrated stories, and they practised planning and goal setting by completing colouring tasks with specific instructions.	The study utilized an executive function test and a Habits of Mind test. The content validity of the Habits of Mind test was reviewed by a panel of five experts, with a content validity index (I-CVI) of 0.90 calculated at the item level.	The experimental group showed significantly higher post-test scores in both Executive Function and Habits of Mind tests compared to the control group, attributed to the use of brain-based instruction.

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				Students were assigned to improve their online research skills, enabling them to analyze data, reflect on it, solve problems, and make timely decisions. They learned how to conduct independent research, assess the relevance of information, analyze issues from various angles, and articulate their opinions, while seminars led by foreign language teachers introduced them to critical thinking strategies.	-students' critical thinking (CT) skills and academic achievement. -Course Questionnaire and exams, which students on argumentative and reflective criteria.	The implementation of BBL techniques resulted in better critical thinking abilities among students in the experimental group compared to the control group. - Experts demonstrated flexible, simultaneous reasoning across stages, while novices followed a rigid, stepwise approach, focusing heavily on facts and learned protocols.
Hassan et al. [40]/ 2023	students / 87	12 major brain compatible learning and three instructional techniques	The study integrated the Synergy model, BBL, and Flipped Classroom approaches to create an ESP (English for Specific Purposes) learning environment.			
Ji & Woo [50]/ 2023	dentists/ 10 experts and 10 novices	BBL model: knowledge representation, clinical decision-making and EEG characteristics	A standardized patient was used to recreate clinical scenarios, and clinical tasks	confirming the patient's complaint, performing examinations, and radiographs.	chief oral reading	-Cortical activities measured through electroencephalogram (EEG) during tasks. -evaluation of clinical decision-making and
Intasena et al.[42]/ 2023	students / 78	BBL management	-experts evaluated learning management - received a very high evaluation.	-10-15 minute activities aimed at enhancing Thai language literacy, reading and writing fluency.		pre-post tests and satisfaction questionnaires to assess outcomes.
						-significantly improved students' Thai language literacy and fluency -high learning

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								experience satisfaction
				- link new words to themes and create unusual associations, which helps enhance engagement and positive emotions through creative and interactive activities.			-brain-based teaching group significantly improved their speaking skills	
Iranmanesh et al.[44]/ 2022	students / 64	12 BBL principles	a computer model of brain connectivity developed using a meta-analysis and 12 brain-based principles to guide instructional processes and activities,	-Pair work and storytelling - network exercises -daydreaming, thinking, and conversing with pen pals, emotionally topics and reflections,	- raters reached a consensus on the pre-test and post-test questions. -Cambridge assessment rubrics -15-minute interview using the Speak Now Testing Program.	-control group also improved, but the change was not significant and was less substantial compared to the experimental group.		
Martin et al.[64]/ 2021	students / 69	The Brain-Based Teaching Approach (BBTA) principles	- Bloom's taxonomy, labs, and self-evaluation tools guide creating tailored simulations, analogies	- BBTA: experiment group; traditional masterclass style: control group -BBTA emphasizes the affective relationship between students and subjects, using cinema, literature, Socratic reasoning, and problem-materials, solving strategies to foster and critical thinking and motivation.	Stroop interference test	-The students not only learn Physics but also develop new ways of thinking. -Significant difference between the groups in the Stroop test,		

				-creating a zero-threat atmosphere, grouping students for collaborative work, and integrating individual ideas into lessons. -vibrant classroom setting: music, experiential learning, and real-life content, ensuring all students had equal opportunities to participate. - The investigators used BBL techniques for the encouraging inquiry, treatment group and promoting physical activity, conventional teaching providing immediate methods for the feedback, and fostering comparison group, creativity by sometimes of employing an Embedded soliciting suggestions from Mixed Methods Design. students.	-MPSA and a Brain-Based Teaching (BBT) with reliability 0.72 using Cronbach's alpha. -case reports from high, moderate, and low achievers of each group -pre- and post-tests to assess the impact of brain-based teaching principles on performance.	-significant difference between the treatment and comparison groups -BBT approach positively influenced the treatment group enhancing higher-order thinking, problem-solving, and meaningful learning. -treatment group experienced a more interactive and engaging learning process, -students who used an embodied personal agent (PA) improved learning outcomes and increased brain activity in social regions -PA led to better retention, transfer, and matching on post-tests, reduced cognitive load
Raghavendran & Begum[75]/ 2021	75 students / 30	12 doctrines BBL	Social theory	agency	-a multimedia lesson on chemical synaptic transmission with or without an on-screen guide that highlighted the graphics during the lecture.	multimedia chemical transmission screen guide	Brain cortical activity was monitored using functional near-infrared spectroscopy (fNIRS), and students' learning was assessed through pre- and post-questionnaires, as well as learning outcome tests.
Li et al.[59]/ 2021	students / 40				lesson on synaptic with an on-		

				-creating an axonometric projection of a 3D composition by modifying			-traditional learning methods: negative frustration and hindered student performance.
				The study investigated clay cubes			-BBL techniques improve
				the application of six -form transformation and BBL principles in visual geometric analysis			performance (deep
				arts and design, adapting -design a 1:1 scale interior -observation.			thinking, planning
				the approach based on a space using real materials and -Skill		development	skills and
				structured evaluation of duct tape.		assessment by analyzing their	creativity) and
		6 BBL principles		student activities, -feedback and hands-on work c			fostering positive
El-Wakeel [30]/ 2020	students / 400	for visual arts and design education		reactions, skills, and activities promote active -comparative analyses and			frustration
				motivation.	processing of experiences,	focused group interviews.	
							-pretest score: 57.65; post-test: 70.41, with an N-Gain of 0.32. This
							demonstrates an
						-logic and set theory	improvement in
						-theorem proof and reasoning,	students' higher-
						targeting high-level thinking	order thinking skills
						skills across conceptual,	through the use of
						procedural, and metacognitive	BBL in logic and
						domains.	set courses.
				The development of teaching materials was		-Pre-test and post-test -	Students who were
		Brain based		carried out using the 4D		Physics Conceptual	exposed to BBT-
		learning models:		method, which includes		Understanding Test (PCUT)	iTBA performed
Lusiana & Andari[62]/ 2020	students / 54	Pattern of the stages of defining, functional brain designing, developing, development and disseminating.			not reported	adapted and modified from the Force Concept Inventory .	significantly better in the PCUT
		-3 BBL foundational elements				-instrument validation by	(including thinking
		-Respects differences	the Validated Brain-Based in Teaching with i-Think			experts, 0.91 (KR-20)	skills, focusing,
Saleh & Mazlan[8 1]/ 2019	students / 180	students appreciate student's	and Maps and the Brain Gym each Approach (BBT-iTBA) lesson plan by experts		Brain-Based Teaching with i-Think Maps and the Brain Gym Approach	reliability value gained from a	reasoning and

							pilot study.		retention) than students who received conventional teaching approaches.
		uniqueness -Brain Gym.							
									-no impact of the program in the first month.
						Integrating alpha and beta brain waves into teaching activities to enhance cognitive and critical skills, creating a balanced, stimulating environment. 10-15 minutes of alpha waves to induce relaxation and 30-35 minutes of beta waves to encourage active thinking.			-average scores of Group A and B increase during second and third month, but Group A score is significantly higher than Group B statistically
				-Group A: exposed to these brain waves through both physical and online teaching sessions, -Group B: no exposure.			evaluations monthly assessments, presentations, and simulations.	conducted through written oral teaching	
Staboulis & Lazaridou [91]/ 2019	students / 40	Computational modelling of cognitive functions				-inquiry phase: introduced to TeamSTEPPS® and share their prior knowledge and			TeamSTEPPS® course knowledge significantly
	paediatric interns	4-phase brain-based lesson plan	brain-based lesson structure in simulation for training	A TeamSTEPPS® implementation plan was applied using a 4-phase assigned		questions about the program. -gathering phase: concepts and competencies supported by literature evidence, case studies, and brief video clips. -process phase: written cases, video scenarios, and high-fidelity simulations,	Pre- and post-intervention data on team performance and knowledge were collected using the validated TeamSTEPPS® tool, learners were surveyed on the value of interprofessional learning and experience.		improved from pre- to post-intervention, and teams demonstrated better performance in the post-intervention simulation cases compared to their pre-assessment
Clapper et al.[18]/ 2019	and nurses/ 23	simulation (inquire, gather, process, apply)		paediatric interns and nurses at an urban academic hospital.					

				debriefing -apply phase: reflect on how to integrate their newfound skills into clinical practice.		results.
Erol & Karaduman[32]/2018	students / 91	-Brain-compatible learning -Brain-friendly learning -BBL	Mathematics teachers and field experts were consulted for planning BBL methods for mathematics education activities.	The activities featured various materials, such as slides, photographs, animations, games, concept maps, mind maps, and assessment questions.	Pre-test and post-test using Mathematics Achievement Test (includes reasoning, thinking with calculation and measurement using numbers of mathematics) were validated by specialist and pilot-tested.	Mathematics achievement and persistence of knowledge from the experimental group is significantly higher in the control group based on the National Education program provided in the textbooks.
Lidiastuti et al.[60]/ 2018	students / 10	12 BBL principles	(1) context analysis (2) design of model based on BBL (3) model validation by experts, simulation and revising model after trials	Examples (images or experiences), auditory elements, cognitive exercises, and repetition based on EXAIR: Example Non-Example model and Auditory, Thinking and Repetition model. Students have breakfast before the lesson	Validation of instruments and product(manual) by experts and teacher	learning model EXAIR based Brain-Based Learning had a significant influence on problem solving skills

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							-students exposed to BBL methods achieved higher academic performance (evaluated memory, understanding, and application based on Bloom's taxonomy.) compared to those in the other group
Al.Ijrish & Naser et al.[3]/ 2018	students / 128	pre-exposure, preparation of the information, explanation, verification, assurance, retention, remembering	and trust,	The researcher applied BBL principles to the experimental group and traditional methods to the control group.	Achievement was assessed using a 30-item multiple-choice test, which evaluated memory, understanding, and application based on Bloom's taxonomy.		-significant improvements post-training, with higher scores in High-Quality CPR and didactic knowledge
Clapper et al.[17]/ 2018	resident physicians and nurses/ 109	4-phase brain-based lesson plan for simulation (inquire, gather, process, apply)	brain-based lesson -evidence -based teamwork, communication, individual skills through interactive simulations.	not reported	-engage in responding to cardiac emergencies through both partial-task and full-body simulations with assessing prior knowledge (Inquire), progressing through gathering new information (Gather), practising skills (Process), and applying them to clinical situations (Apply). -utilize evidence-based topic sheets, engage in	Pre- and post-course assessments of CPR and code team knowledge, as well as performance in mock code simulations.	-in-situ team performance improved, especially in cardiac code

				collaborative learning, and receive ongoing feedback			management during the day shift, where the "done well" percentage significantly increased
Solomon et al.[89]/ 2017	students / 42	cognitive learning principles	The "Tailored Instructions Engineered Using PROTOCOLs" (TIED-UP) was created with 9 key concepts from BBL in response to a pilot study	Each course concept is divided into interconnected sub-concepts, with short instructional videos developed for each one. These videos follow specific mandatory instructional protocols to enhance learning. repeated and reinforcement of foundational Delivery concepts and assistance before they entering these higher-level approach classes in honing their basic mathematical skills before can effectively participate in their coursework	pre-knowledge (comprehension prerequisite material mathematical abilities) experiment and 4 tests experiment	test framework of outperformed their and peers in class tests before compared to those after in the control group.	The TIED-UP course delivery framework aims to address student disengagement issues resulting from inadequate instruction. Students taught using this

				-intended goals of learning are communicated, -suggest alternative purposes -Establishing learning objectives before engaging in activities -reading (texts, graphics, tables), interpreting images, accessing online resources, completing tasks, questions, conducting inquiries, and taking notes.			The average critical thinking test scores for the experimental and control groups were 4.29 and 6.02, respectively. A t-test revealed a significant difference between the groups with a p-value of 0.037. Part 1: The experimental group showed significant improvement in both working memory (WM) areas, leading to better reasoning test performance, which persisted 16 weeks post-training. Part 2: WM training alone did not improve reasoning, but independent reasoning strategy training led to significant gains after the intervention.
Utomo[99]/ 2016	/ not reported	Activities, Resume)	Model A-CAR (Activation, Confirmation, and	Learning is using the Activation, Confirmation, and Summary.	structured sequence: Activities,	Critical thinking skills are assessed through specific elements included in the critical thinking test questions.	
Aries et al. 2015	[4]/ 92, 2: 63	students / Part 1: Part 2:	combination of cognitive and meta-cognitive strategies	A combined intervention focusing on working memory (WM), cognitive function, and meta-cognitive function engaged in guided discussions and capacity, as well as reasoning strategies from previous studies, was implemented.	cognitive tasks (n-back task and Odd One Out task); a meta-cognitive task, the IMPROVE method was used, where participants worked in small groups to solve complex reasoning questions and to internalise problem-solving strategies, with providing brief assistance during each problem.	The tests and exams, which included theoretical expertise questions and 10 reasoning questions, were compiled and reviewed by three history teachers. Two weeks before the testing, the school tests were also evaluated by teachers from the control group.	

Demirhan et al.[26]/ 2014	teachers / Part A: 65, Part B: 9	12 BBL principles plus foundational elements	3 methods.	-Part A: comparing BBL with conventional -Part B: Interviews to explore their perceptions of the BBL approach.	- models, visuals, and animations were incorporated, allowing students the option to study independently or in groups. Created posters and PowerPoint presentations, and had the opportunity to work individually or collaboratively on a chosen project, including open-ended laboratory experiments. -permitted to drink water and have snacks during class, and they	-Part A: Pre- and post-tests, including the Biology Achievement Test and Critical Thinking Disposition Inventory, were administered. -Part B: Interviews	Part A showed no significant impact of the teaching method on achievement, attitude, critical thinking disposition, and self-efficacy scores. However, Part B indicated that brain-based teaching has a somewhat significant influence on cognitive, affective, and metacognitive aspects.

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Table 2. Summary of descriptive studies utilizing surveys or interviews involving participants

(A)/ Year	Ps / n	Principles/Cognitive Theory	Development Of Study Instruments	Outcome
Siming & Abraha [88]/ 2023	instructors/ Quantitative: 512, Qualitative: 14	12 BBL principles	A questionnaire, grounded in the twelve principles of BBL theory, was pilot-tested and validated by experts. Semi-structured interviews were then crafted with guiding questions aligned with the research questions and the same BBL principles.	Most natural science and engineering instructors are familiar with brain-based instruction (BBI), but they often struggle to apply this knowledge in practical skills. Regardless of their awareness of BBI, many instructors struggle with applying these concepts effectively. knowledge and skills.
Darmawan et al.[23]/ 2022	students/ 250	elements of BBL in history teaching, i.e., cognitive, social, physical, reflective, and emotional aspects	The questionnaire surveyed students on the elements of BBL in history instruction, focusing on cognitive, social, physical, reflective, and emotional aspects of the approach. It utilized a 5-point Likert scale. In addition to the questionnaire, data were gathered through observations and student interviews. Observations took place over two months, covering six class sessions for each group. Interviews were conducted with 10 selected students from each class after the conclusion of the course.	Survey findings: The BBL approach effectively aids educators in understanding student characteristics and fostering a collaborative classroom environment that enhances historical reflection and fact memorization. However, it falls short in addressing students' emotional intelligence, historical empathy, and stress management, leaving them anxious about memorizing large amounts of historical data and lacking guidance on expressing their feelings about historical events.

Fragkaki et al.[34]/ 2022	academics/ 60	didactic neuroscience-based principles of attention, dual coding, engagement, emotions, creativity, and critical thinking	The questionnaire, one of the first of its kind, was developed using neuroscience-based teaching principles, including attention, dual coding, engagement, emotions, creativity, and critical thinking. It aimed to systematically assess the prior knowledge, opinions, and needs of university faculty in neuroeducation.	Academics acknowledge the value of neuroeducation training and the practical use of neuropedagogy in teaching. However, their stated teaching beliefs and theoretical principles often do not fully align with their actual teaching practices.
Yudha et al.[106]/ 2020	students/ 32	7 stages of brain-based planning	teacher observation sheets manage learning, observation sheets of student activities, tests of students' mathematical literacy abilities, and student questionnaire responses after learning	Students' ability of mathematical literacy (Classical completeness) that includes reasoning and argument obtains 92% value (effective) after learning BBL .
Wu & Xie[101]/ 2018	teachers and students/ 31 teachers, 420 students	Theory of Brain Science (Whole brain theory, Emotional brain theory and Neural plasticity theory)	The study investigated brain-based teaching in college English classrooms, integrating the literature-based Whole Brain Teaching strategy (analytical thinking, organizational thinking, communicative thinking and fantasy thinking) , Emotional teaching strategies, and Environmental strategies. Data were gathered through a questionnaire survey to analyze the effectiveness of these approaches.	-Students with higher English achievement and longer learning periods gave more positive feedback on brain-based cognitive teaching strategies, while teachers were aware of key aspects but lacked deep knowledge of brain science. -Emotional strategies were rated highest, followed by environmental and whole-brain strategies, highlighting the need for better understanding of brain function to improve teaching effectiveness and proposing a brain cognition-based teaching model for higher education.

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Abidin et al.[1]/ 2017	teachers/ 5	Principles of BBL	This qualitative study used interviews with teachers and classroom observations. The interview questions were developed based on insights from a literature review. Classroom observations were conducted to examine behaviours and understand the teaching and learning environment for Slow Reader Students (SRS), with observers maintaining a non-intrusive role during the observations.	Develop a serious game model for Slow Reader Students, incorporating short, repeatable exercises with interactive sound effects, colourful graphics, and feedback, ensuring the appropriate use of colour contrasts to enhance focus, engagement, and performance in literacy skills.

Table 3. Overview of content analysis and observational studies without participants

(A)/Year	Principles/ Cognitive Theory	Development of BBL Materials	Learning Activities	Thinking Skills
Onello [72]/ 2023	Preview-Review-Synthesize framework	-A scaffolded approach, utilising a faculty-designed Preview-Review-Synthesize framework, encouraged active engagement with course content outside of class, integrating BBL principles. -Learning Guides helped shift students' focus from "what" to "how" they study, with initial feedback from nursing students indicating their effectiveness in supporting learning.	-The Preview section of each Learning Guide utilised brain science principles to enhance student readiness through activities such as structured pre-reading, reviewing prior knowledge, and metacognitive exercises. -The Review and Synthesize sections reinforced learning by promoting active engagement, clarifying content, and integrating knowledge through evidence-based strategies.	not reported

Sari et al. [83]/ 2021	7 stages of brain-based planning	-The process begins with requirements and context analysis, followed by the prototype-making phase, which includes design, development, and formative assessments such as expert reviews, personality assessments, and field tests. -Findings indicate that BBL-based mathematics learning tools are valid and practical for teaching sine and cosine to 10th-grade students.	not reported	mathematical creative thinking skills
Hambley[38]/ 2020	CONNECT© model	-The aim is to differentiate scientific facts from fiction by identifying key brain science concepts relevant to clients and translating them into practical skills and behaviors. The CONNECT model provides a framework for integrating "brain-friendly" strategies, incorporating Seven Brain Dynamics and emphasising core principles such as Consistency, Ownership, Novelty, and Trust.	-Clear expectations, transparent communication, and structured guidance create certainty, while delegating responsibilities and encouraging input foster ownership and engagement. -Aligning individual strengths with organisational goals, promoting inclusivity, and fostering a learning culture enhance employee confidence, creativity, and commitment.	not reported
Rahman et al.[76]/ 2019	BBL model for mathematics learning	An e-module for English for tourism is being developed using the BBL approach. The development follows the research and development (R&D) model by Dick and Carey, combined with the Hardiman Meriale Model. The English for tourism e-module, based on a BBL approach, emphasizes the four key communication skills: speaking, listening, reading, and writing.	-The researcher curates and adapts English materials for tourism from textbooks, course books, and online resources to align with educational objectives. -The instructional approach employs six brain-targeted strategies, including creating a supportive environment, integrating prior knowledge, emphasising mastery, fostering creativity, applying real-world contexts, and utilising ongoing assessments to enhance learning and retention.	not reported
Susanti et al.[93]/ 2019	Mathematics thinking in Brain-	Modified 4-D model (define, design, and develop) and involved validation sheets, legibility validation, and student response questionnaires. Brain-based cooperative learning	not reported	critical thinking

	Compatible Teaching and Learning	tools, particularly student worksheets, were deemed valid by experts and effectively improved students' critical thinking skills, with 76% of students showing progress and an 81.23% success rate exceeding the minimum criteria.		
Mensan & Osman [68] / 2018	7 stages of brain-based Planning	Pre-exposure, Preparation, Initiation and acquisition, Elaboration, Incubation and memory encoding, Verification and confidence check and Celebration and integration.	Pre-exposure to new material, followed by preparation activities that spark curiosity and hands-on engagement. Students then acquire and integrate information through discussions and elaboration. Reflection, verification, and confidence checks reinforce learning, while celebration and integration stages reward achievements and foster long-term engagement.	critical thinking
Sestito et al.[87]/ 2018	Embodied cognition: Mirror Neuron system	A new interdisciplinary approach integrates ecological psychology, embodied cognition, and neurophysiological frameworks to explain human performance patterns in various aviation contexts. The analysis identifies three future research and application areas.	(1) improving flight training by examining specific agent-environment interactions, (2) monitoring training progress through brain patterns related to flight expertise, and (3) designing advanced human-machine interfaces for flight decks using principles from neuroscience.	not reported
Dai et al.[21]/ 2018	Full time-space infiltration teaching system model	The study combines the macro-micro principle of brain cognition with various factors influencing civil engineering education to develop a full-time, space-infiltrating teaching model. This model introduces strategies to enhance classroom efficiency and effectiveness, making teaching more scientific and productive. A key element of the model is the concept of selective attention, where teaching content is designed to be more easily noticed and processed by the brain, aligning with brain-based cognitive teaching methods.	-Platforms like Moodle enable personalised learning and teacher-student collaboration, while YouTube enhances engagement by capturing students' attention. -Using multimedia tools, humor, and cooperative learning strategies fosters an interactive environment that encourages participation and deeper understanding	not reported