Review Article

Concept Mapping in ESL/EFL Education: Cognitive and Affective Processes, Learning Outcomes, and Implications for School-Age Learners

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Abstract

Concept mapping is a visual learning strategy that can support the organisation, integration, and retrieval of linguistic knowledge. Its implications extend beyond language achievement to cognitive processing, academic motivation, self-efficacy, classroom participation, and learning-related anxiety. This narrative review synthesises theoretical, meta-analytic, and empirical evidence concerning concept mapping in second- and foreign-language (ESL/EFL) education, with particular attention to developmental implications for school-age learners. It distinguishes Novakian concept mapping from mind mapping, semantic mapping, and other visual organisers, and examines instructional formats, language outcomes, cognitive and affective processes, moderators, and practical constraints. A meta-analysis of 68 L2 studies reported a large mean effect on language achievement (Hedges' g = 1.047), although heterogeneity was very high and effects were smaller in primary than secondary settings. Evidence concerning psychological outcomes is more limited: positive findings for speaking anxiety and confidence often come from tertiary learners, whereas school-age studies have reported mixed or null effects. Guided mapping may facilitate metacognitive reflection and peer collaboration, but poorly scaffolded tasks can increase cognitive demands and frustration. Importantly, language-learning anxiety, classroom confidence, and psychological well-being are distinct from clinically assessed mental health outcomes; current evidence does not establish concept mapping as a treatment for childhood mental health disorders. Future research should prioritise age-specific designs, validated affective and well-being measures, developmental moderators, and longer-term follow-up

Keywords: Concept mapping; ESL/EFL education; educational psychology; school-age learners; cognitive load; language-learning anxiety; self-efficacy; psychological well-being

1. Introduction

Concept mapping is a long-standing instructional strategy that promotes deeper language learning. Originating in science education, Joseph Novak and colleagues at Cornell first developed concept maps in the 1970s to make students' conceptual structures visible (Novak & Musonda, 1991). A concept map is defined as "a schematic device for representing a set of concept meanings embedded in a framework of propositions". In practice, it is a simple graphical network (nodes and labelled links) that encourages learners to organise relationships hierarchically. This visual format encodes complex ideas in an accessible way, enabling learners to connect new language input to prior knowledge and to plan meaningful output in a more structured form.

In language classrooms, educators have used concept maps to support a range of skills. For example, researchers have found that concept mapping aids vocabulary acquisition (Bahr & Dansereau, 2001) and reading comprehension (Liu et al., 2010). Others report benefits for writing and speaking performance (Ojima, 2006; Wang & Liao, 2014; Chen & Hwang, 2020). Some studies have also used computerised mapping tools to foster listening skills and grammar learning. Over the last two decades, the concept-mapping literature in ESL/EFL has grown enormously, spanning small quasi-experiments, larger experimental trials, and several reviews. A key review by Nesbit and Adesope (2006) found a large mean effect (g = 0.82) of concept mapping on learning across domains. More recently, Han's (2025) meta-analysis of 68 L2 studies (N = 14,656) reports an even larger effect (g = 1.047) of concept mapping on language outcomes. Similarly, a systematic synthesis of computerised concept mapping in language learning by Li and Li (2025) shows that research has steadily tracked how mapping has been used in relation to learning objectives, methods, tools, and strategies over the past 20 years.

However, beneficial effects should not be assumed across all learners or outcomes. Some studies report modest or nonsignificant differences, and time-intensive or complex maps may impose additional cognitive demands (Hwang et al., 2019; Li & Li, 2025). This is a narrative synthesis, not a new systematic review or meta-analysis. It first examines foundational theories and mapping formats, then considers language achievement alongside psychological and affective processes. School-based evidence is distinguished from research in tertiary or adult samples, and learning-related anxiety is distinguished from clinical mental health outcomes. Given the marked heterogeneity in L2 effects (Han, 2025), the review emphasises developmental appropriateness, instructional support, and unanswered questions about psychological well-being in children and adolescents.

2. Theoretical Foundations

Concept mapping in language education draws on several complementary learning theories (Figure 1). Ausubel's theory of meaningful learning is often cited as the primary foundation. Ausubel (1968) argued that new information must be subsumed under existing cognitive structures for genuine understanding. In practice, meaningful learning involves perceiving a new concept and its linguistic label, and linking them to prior knowledge, rather than memorising in isolation. Novak (1990) developed the concept-mapping technique to realise Ausubel's ideas by explicitly drawing hierarchical maps of old and new concepts; learners actively connect and integrate knowledge. This process aligns with Ausubel's notion that learning is a continuous cognitive process of expanding, modifying, and organising one's schemata. In second-language (L2) contexts, vocabulary and grammar are acquired more durably when they are meaningfully attached to existing schemata. In contrast to rote memorisation (e.g., learning disconnected word lists), Ausubel warned that purely repetitive learning yields only superficial recall (Ausubel, 1968). Concept mapping encourages deep processing by prompting learners to find meaningful links between what they already know and new language forms. For example, Han (2025) describes concept mapping as a "continuous cognitive process" of elaborating old concepts as new relationships are added. Thus, concept mapping aligns with Ausubel's theory of meaningful learning by engaging students in recognising, organising, and explicitly representing relationships among concepts.

Paivio's (1986) dual coding theory offers another lens. He proposed that verbal and visual information are encoded in separate but interacting systems. When a learning task engages both channels simultaneously, retention is enhanced. Concept maps naturally engage both channels, processing verbal labels (words, sentences) and encoding the spatial arrangement of concepts. Kulhavy et al. (1985) formalised this idea as the conjoint retention hypothesis, noting that paired verbal and visual representations create two parallel memory traces (one linguistic, one pictorial). In practical terms, a semantic map of vocabulary means that learners not only store the word and its meaning but also remember the map's structure as an extra cue. Bahr and Dansereau (2005) empirically demonstrated this benefit. Bilingual concept maps (words presented in two languages on a shared map) improved delayed recall of foreign vocabulary by providing rich encoding cues. In other words, the map's images and layout offer a second retrieval path, consistent with Paivio's theory. This dual-channel processing is closely related to Mayer's (2005) cognitive theory of multimedia learning, in which instruction that integrates words and pictures deepens understanding. Concept mapping can be seen as an application of multimedia learning principles, since it embeds verbal and non-verbal representations in a single coherent graphic.

Schema theory (Bartlett, 1932; Rumelhart, 1984) is also fundamental. It holds that prior knowledge is organised into abstract mental frameworks (schemata) that guide comprehension and production. Concept mapping explicitly activates schemata by prompting learners to brainstorm and organise all relevant knowledge on a topic before engaging with new input. In other words, creating a map makes latent schemata visible and foregrounds the learner's own knowledge structures. Ojima (2006) found that concept mapping, as a pre-task planning strategy, helped ESL writers by activating and extending their existing writing schemata. Similarly, Wang et al. (2011) emphasise that knowledge-visualisation tools support self-regulated learning by making schemata explicit and manipulable. In their study of an online course, they showed that visualising the domain knowledge (essentially drawing a map of the subject) made it easier for students to see and manage connections among concepts. Thus, concept mapping operationalises schema theory; it prompts learners to retrieve prior knowledge (schema), group related ideas, and link them in a structure that can be revised. The resulting map both reflects and refines the learner's internal schema, facilitating comprehension of new material.

Cognitive elaboration theory by Wittrock (1974) offers a final perspective. He proposed that active learners build meaning by restructuring and elaborating information, comparing and contrasting it, and connecting new ideas to known concepts. Concept mapping fosters exactly this kind of generative learning; students must chunk information, determine relationships, and reorganise content into a hierarchical visual format. In doing so, they engage in higher-order thinking. For example, learners using concept maps must evaluate which concepts are primary, define linking propositions, and consider cross-links, tasks that involve analysis and synthesis. Chen and Hwang's (2020) study of a flipped classroom using concept mapping found that students generated richer outlines and reflected more deeply on their learning outcomes, consistent with elaboration theory. Concept mapping reflects Wittrock's generative learning theory by encouraging learners to actively connect new information with prior knowledge.

2.1 Cognitive Load, Self-Efficacy, and Self-Regulated Learning

Cognitive load theory offers a complementary account of how visual mapping may influence learning. Working memory is limited; an overly complex or unfamiliar map can increase extraneous demands, whereas a well-structured map may support the integration of related ideas and reduce unnecessary search (Sweller, 1988). Concept-map preparation therefore does not necessarily lower cognitive load. Studies of guided mapping and digital interfaces indicate that load and delayed retention can respond differently to particular task designs (Furtado et al., 2019; Li et al., 2025). For younger learners, the distinction between providing a partly completed map and requiring an open-ended map may be particularly important.

Social cognitive theory also highlights academic self-efficacy: learners' beliefs about their capacity to perform a specific task can influence effort, persistence, and response to difficulty (Bandura, 1997). Concept mapping may offer visible evidence of progress and a structured plan for language production, but improved performance does not automatically imply improved self-efficacy. From a self-regulated learning perspective, mapping can be used to plan, monitor comprehension, identify missing links, and revise explanations (Zimmerman, 2002). In a junior-high intervention, instruction in map construction improved learning outcomes and map quality and produced a small improvement in the accuracy of students' self-evaluation (Lenski et al., 2022). These theories identify plausible mechanisms rather than demonstrating direct mental health benefits.

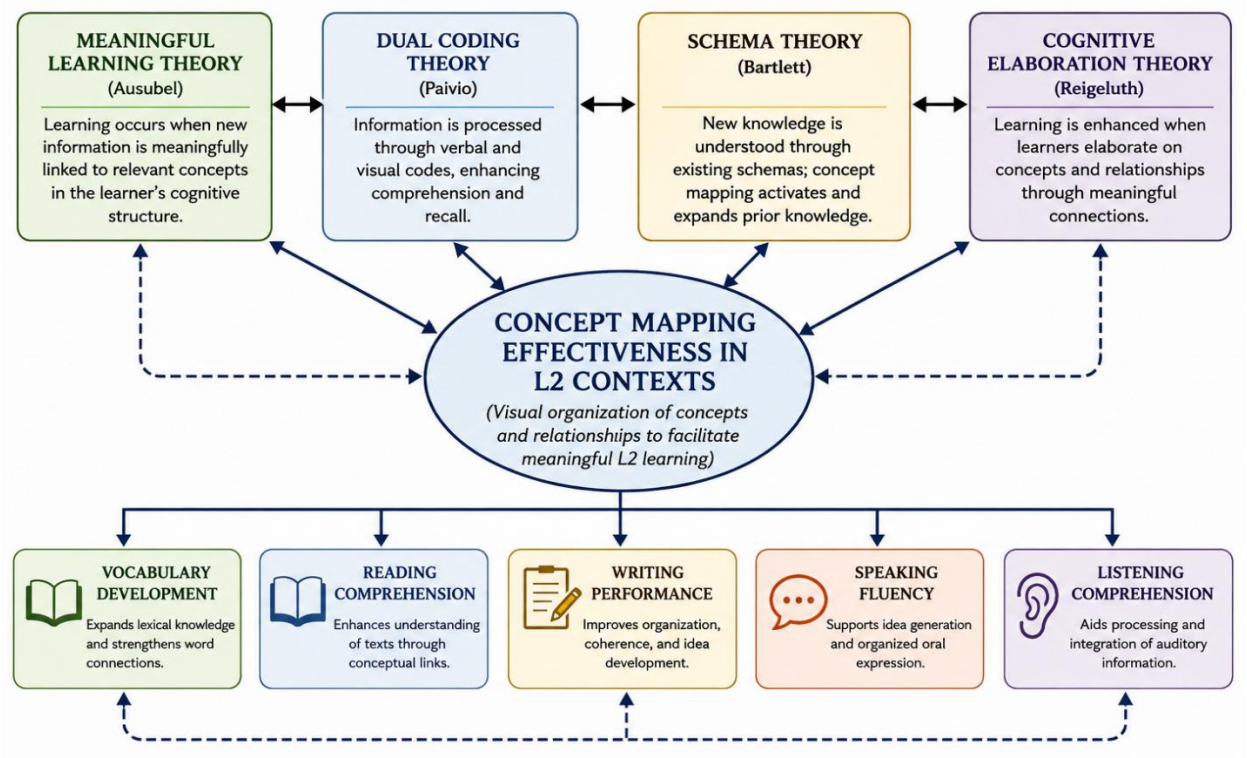

Figure 1. Foundational learning theories underpinning concept mapping in ESL/EFL education

3. Distinguishing Concept Mapping from Related Tools

A persistent issue in the literature on visual learning tools is the interchangeable use of terms such as concept mapping, mind mapping, semantic mapping, graphic organisers, and argument mapping (Figure 2). Davies's (2011) taxonomy highlights that, despite superficial similarities, these tools differ markedly in structure, purpose, and cognitive demands. Each mapping technique serves a specific instructional goal. Some promote free-form idea generation, others emphasise hierarchical relationships, and still others formalise logical argument structures. Table 1 illustrates these key differences; the remainder of this section elaborates on each tool and cites representative applications in L2 learning.

3.1 Mind Mapping

Mind mapping, formalised by Buzan (1974), is a radial, non-linear diagram centred on a central concept. In a mind map, the central idea (often depicted with an image or keyword) has branches radiating to related concepts or associations. Lines connecting nodes are typically unlabelled; the structure is loose and "organic," allowing any idea to link freely to any other. This flexibility promotes creative, associative thinking and makes mind maps powerful tools for brainstorming and free-form planning. For example, language teachers have used mind maps for vocabulary ideation and for prewriting or speech-planning activities, in which students rapidly generate related words or topics around a theme.

However, mind maps trade formal structure for flexibility. Because links are unlabelled and branching is unconstrained, mind maps cannot easily represent precise relationships or hierarchical order. Davies (2011) notes that mind maps "outline only hierarchical relationships (in radial form)" and are idiosyncratic in design, making them difficult for others to interpret. In practice, mind maps tend to highlight associations, but they do not make explicit the nature of the relationship (e.g., cause-effect or part-whole). As a result, their benefit lies chiefly in idea generation and recall (many learners find visual brainstorms memorable), but they are limited when a task requires understanding complex conceptual relationships.

3.2 Concept Mapping (Novakian)

Concept mapping in the Novak & Gowin (1984) tradition is a formal, hierarchical diagram. A Novakian concept map begins with a focus question or central topic at the top. Concepts (usually brief noun phrases) are arranged in descending levels of specificity and connected by labelled links that specify the nature of each relationship (for example, "causes," "is part of," "leads to"). Each pair of connected concepts, together with its link, forms a meaningful proposition, a statement about the relationship. Cross-links between different branches are especially valued, as they indicate integrative understanding across subdomains.

Unlike mind maps, concept maps do not rely on pictures or free association. They are explicitly designed to outline conceptual structure rather than to generate ideas at random. As Davies (2011) explains, concept maps are "more structured and less pictorial in nature" than mind maps. A concept map's tree-like hierarchy reflects Ausubel's principle that new knowledge should be anchored to existing schemata. In language learning, this means that vocabulary, grammatical items, or discourse elements are learned in relation to other concepts rather than in isolation. For example, mapping the relations between thematic vocabulary sets or linking language skills to contexts helps learners organise knowledge systematically. Explicitly labelling each link requires learners to articulate how their language concepts connect, deepening understanding beyond rote memorisation.

3.3 Argument Mapping

Argument mapping is a specialised form of diagramming that focuses on the inferential structure of reasoning rather than general concept relations. An argument map represents claims, reasons, objections, and rebuttals in a hierarchical network. In practice, boxes or nodes denote propositions (e.g., assertions or supporting facts), and arrows connect them with logical linkers such as "because," "however," or "therefore." This box-and-arrow convention makes the map explicitly about why something is true (the justification), not just how concepts are related. As Eftekhari et al. (2016) describe, argument mapping "follows a specific set of conventions" in which boxes represent claims and reasons and arrows indicate argumentative moves. The goal is to visualise reasoning chains and their validity.

Because argument maps are inferential tools, they are particularly useful for advanced reading and critical-thinking tasks. For example, Eftekhari et al. (2016) used computer-aided argument mapping in an EFL writing course to train

students in inductive reasoning and critique. Whereas concept mapping highlights relations between ideas, argument mapping highlights logical relations between claims. In language learning, this distinction matters. An argument map may help advanced learners structure an essay or debate by tracing evidence and counterarguments, whereas a concept map helps them understand how language concepts fit within a broader topic.

3.4 Graphic Organisers and Semantic Maps

A graphic organiser is an umbrella term for structured diagrams such as flowcharts, matrices, or sequence charts that arrange information according to text structures (such as cause–effect, compare–contrast, and chronology). For example, a cause-effect organiser might list causes on one side and effects on the other, linked by labelled arrows. These tools usually don't rely on free associations; instead, they impose a template on a particular rhetorical pattern, helping you understand a text's structure.

Semantic maps (sometimes called semantic webs or word maps) focus on vocabulary. A central concept or theme sits at the centre, with related words or subcategories radiating outwards, often grouped by meaning. For example, a semantic map for "weather" might branch into categories such as precipitation and temperature, with words like rain, snow, hot, and cold attached. The aim is to cluster new lexical items with related concepts, drawing on learners' existing mental networks of meaning.

In practice, surveys of computerised concept mapping research indicate that these tools are actively used in language education. A bibliometric review found that concept mapping tools were most frequently employed in CCMLL (Computerised Concept Mapping for Language Learning) studies, followed by mind mapping, graphic organisers, argument mapping, and semantic mapping (Li and Li, 2025). This ranking confirms that teachers commonly distinguish these tools by purpose; vocabulary and theme development often use semantic maps and mind maps; reading and writing strategies often use concept maps and graphic organisers; while advanced critical thinking tasks may use argument maps. Together, these distinctions clarify that concept maps (Novakian) are neither identical to nor superior to all other graphical tools; they are one type of visual organiser, specialised for relational understanding. Mind maps excel at brainstorming, argument maps at reasoning, and graphic/semantic organisers at structuring text or vocabularies. A thorough synthesis of the literature therefore treats each mapping tool separately. In this review, we will consider "concept mapping" in the Novakian sense, while acknowledging related tools where relevant.

Table 1. Comparative summary of knowledge mapping tools in ESL/EFL education

Feature	Concept Map	Mind Map	Argument Map	Graphic Organizer	Semantic Map
Primary purpose	Relational understanding and representation of meaningful relationships among concepts.	Creative association and brainstorming around a central idea.	Analysis and visual representation of arguments, including claims and supporting reasons/evidence.	Organising and visually representing information, relationships, and text structure.	Vocabulary development and organisation of semantically related concepts/words.
Structure	Hierarchical/network structure, generally progressing from more general to more specific concepts.	Radial structure with branches extending from a central concept.	Structured argument diagram showing relationships among claims, reasons and objections.	Varies according to type: Venn diagrams, flowcharts, T-charts, matrices, etc.	Web/network structure in which a central word or concept is connected to related categories and terms.
Linking devices	Lines/arrows with labelled linking words or phrases expressing relationships between concepts.	Branches/lines connecting keywords and ideas; links generally do not	Explicit directional links showing support, objection,	Arrows, lines, boxes, circles and other graphic conventions	Lines/branches connecting words according to semantic/category relationships

		function as explicit propositions.	reason, evidence or other argumentative relationships.	depending on the organiser	
Language/register	Conceptual and relational; may support relatively precise academic language because relationships are explicitly labelled.	Keyword-oriented and comparatively flexible/associative.	Precise and analytical, requiring explicit formulation of claims and reasons	Structured and task-dependent; language varies according to the type and purpose of the organiser	Vocabulary- and category-oriented; language is organised around semantic relationships
Primary L2 skill application	Reading comprehension, writing, vocabulary/ concept development, and integrated language learning.	Brainstorming, vocabulary development, planning and pre-writing.	Critical reading, analytical writing and reasoning.	Reading comprehension, writing organisation, pre-reading, post-reading and study skills.	Vocabulary learning, pre-reading, post-reading and word-relationship development.
Key software/ tools	CmapTools; Inspiration; XMind	SimpleMind; MindMeister	Rationale; Argunet/Argumaan	Kit-Build; Frayer Model *(the latter is a strategy/template rather than software)*	Semantic-mapping tools and general concept/mind-mapping software; software examples should be specified cautiously.
Key theoretical basis	Ausubel's meaningful learning theory; cognitive/constructivist foundations of concept mapping.	Association and radiating thought principles associated with Buzan's mind-mapping approach.	Argumentation and reasoning theory; argument structure and critical-thinking frameworks.	Schema theory and visual representation approaches can provide theoretical support, but graphic organisers constitute a broad category rather than a single theoretically unified tool.	Semantic organisation/network approaches to vocabulary and prior knowledge; semantic mapping is particularly associated with vocabulary and reading instruction.
References	Bahr & Dansereau, 2001; Novak, 2002; Novak & Cañas, 2006; Davies, 2011	Buzan, 1974; Davies, 2011	Davies, 2009, 2011; Dwyer et al., 2010	Darch & Eaves, 1986; Heimlich & Pittelman, 1986	Heimlich & Pittelman, 1986; Udaya, 2022

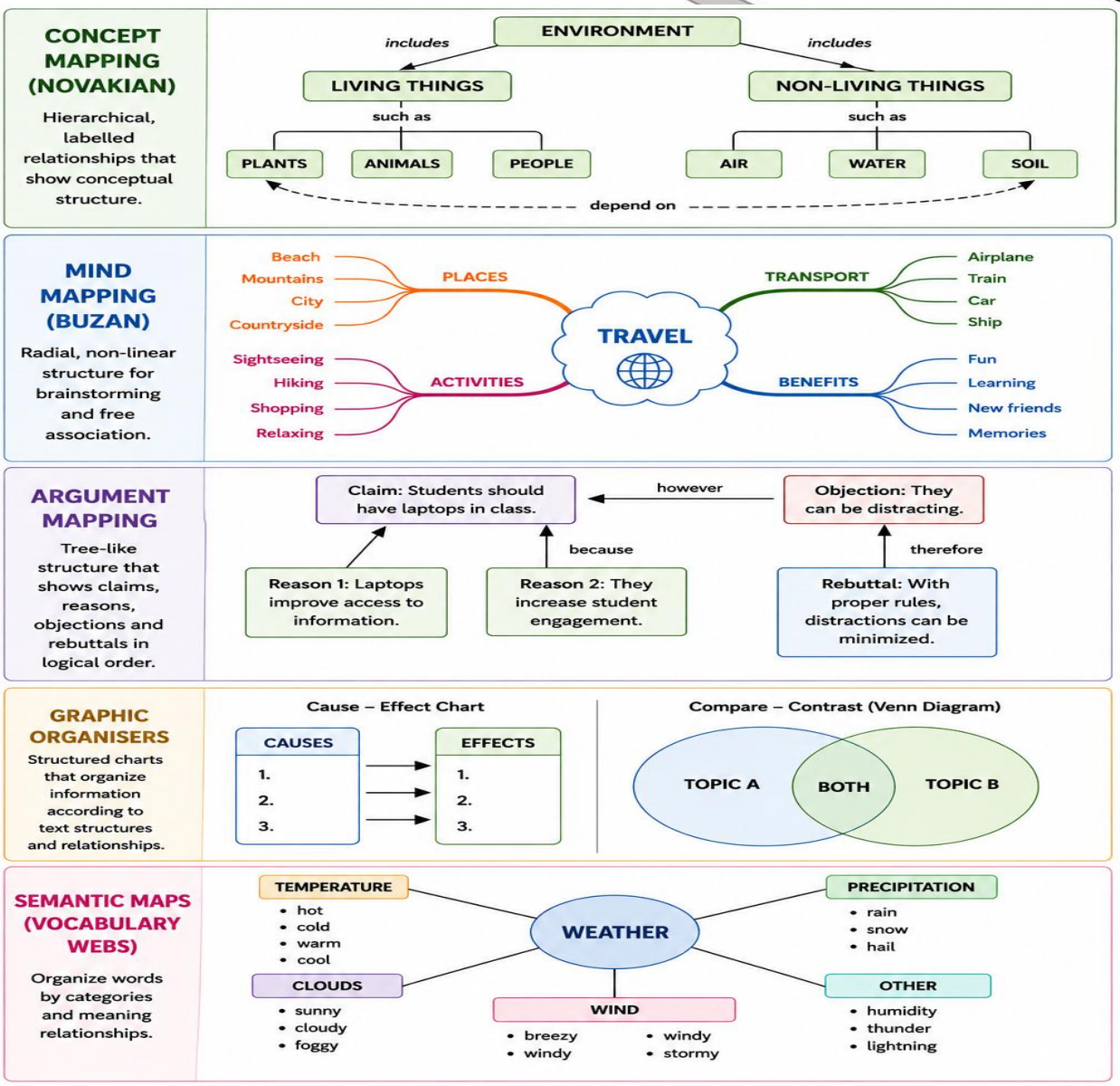

Figure 2. Visual representation of knowledge mapping tools in ESL/EFL education

4. Instructional Formats and Technology Integration

The manner in which concept mapping is implemented, whether paper-based or computerised, individual or collaborative, embedded in flipped learning or conventional instruction (Figure 3), has emerged as a significant moderator of its effectiveness.

4.1 Paper-Based vs Computerised Concept Mapping

A meta-analysis found that paper-based concept mapping produced a much larger effect on L2 outcomes (g = 1.499) than computerised concept mapping (g = 0.892) (Han, 2025). Paper-based mapping involves learners drawing their maps by hand, which, although more time-consuming and harder to edit, may foster deeper engagement. Harrell (2008) argues that the manual act of map construction "engages deeper cognitive processing," especially critical thinking, and Liu (2011) similarly found that the slower, more deliberate process of hand-drawing concept maps leads to deeper processing of relationships between concepts in writing tasks.

Computerised concept mapping offers practical advantages, including easy revision, effortless sharing (for example, via a Learning Management System, LMS), and the potential for immediate feedback. Strickland & Lin (2003) reported that computer-based mapping facilitated idea generation in prewriting, and Yang (2015) found that digital maps led to greater gains in reading comprehension and summary skills than paper maps. Importantly, Chen and Hwang (2020) showed that computerised maps yield maximal benefit when used within a structured pedagogical framework (such as a flipped classroom) that leverages their dynamic features. Thus, both formats offer distinct advantages; digital tools facilitate efficient editing and collaboration, whereas paper-based mapping may support deeper cognitive processing. Therefore, educators should consider the instructional context and learning objectives when selecting the most appropriate mapping format.

4.2 Individual vs. Collaborative Concept Mapping

Concept mapping can be done individually or collaboratively, and this choice also influences learning outcomes. Individual mapping allows each learner to externalise personal knowledge structures, making their schemas visible for self-assessment or teacher feedback. For example, Horton et al. (1993) found that when students create concept maps on their own, their learning improves and their attitudes towards the content become more positive. Collaborative mapping, in turn, engages learners in negotiation and co-constructing understanding. van Boxtel et al. (2002) observed that students working together on maps perform more "elaborative actions and negotiation of meanings," generating richer interactions and deeper learning.

Consistent with these findings, a meta-analysis reported slightly larger effect sizes for group formats (cooperative/collaborative mapping, $g = 1.543$) than for individual mapping ($g = 1.283$), though the difference was marginal ($p \approx .05$) (Han, 2025). In practice, many researchers advocate combining approaches. Novak (2010) suggests that learners first create concept maps individually and then share them to build a group map. This sequenced approach capitalises on the benefits of both modes, individual reflection and collaborative meaning-making. Both formats contribute to learning in different ways; collaborative mapping often promotes greater elaboration through social interaction, whereas individual mapping provides insight into each learner's knowledge structure and schema.

4.3 Concept Mapping in Flipped Learning

Embedding concept mapping in a flipped classroom has emerged as a powerful instructional model. In a flipped design, students first acquire basic content via videos or readings, and class time is then devoted to active work. When that active work involves constructing concept maps, students must synthesise their pre-class input into a coherent visual framework that scaffolds subsequent speaking, writing, or discussion tasks. For example, Chen and Hwang (2020) conducted an 18-week quasi-experiment with 72 university EFL learners. The group using a concept-mapping–based flipped approach significantly outperformed the conventional flipped group on multiple measures, including listening comprehension (adjusted means 74.09 vs. 68.59, $F=9.31$, $p<.01$), speaking performance (8.23 vs. 7.01, $F=28.85$, $p<.001$), and critical thinking awareness (3.98 vs. 3.63, $F=7.42$, $p<.01$). These results suggest that in-class mapping activities help learners organise pre-learned content and apply it more effectively. In addition, Li and Li (2025) identified concept-mapping–enhanced flipped learning as one of the most prominent strategies emerging in recent computerised concept mapping for language learning (CCMLL) research. Thus, current evidence indicates that integrating mapping into flipped instruction can substantially boost listening, speaking, and higher-order thinking outcomes.

4.4 Digital Tools and Platforms

A range of software platforms supports computerised concept mapping in L2 education. Reports show frequent use of tools such as Inspiration, CmapTools, XMind, Mindomo, Airmap, and CohViz for general concept maps; Kit-Build concept map for guided mapping; SimpleMind for freeform mind maps; Rationale for argument maps; the Frayer Model for vocabulary; and SchematicMind for semantic maps. Recent innovations have pushed the technological frontier further. For example, Mubarok et al. (2024) introduced a virtual reality–based argument mapping approach, and Lin and Mubarok (2021) developed a mind map–guided AI chatbot for flipped speaking classes. These emerging platforms highlight how CCMLL is expanding beyond traditional desktops. Thus, the selection of a digital mapping tool should be guided by the intended learning objectives, such as using argument mapping to develop critical reasoning or semantic mapping to support vocabulary development, while incorporating features such as collaboration, multimedia integration, and adaptive feedback.

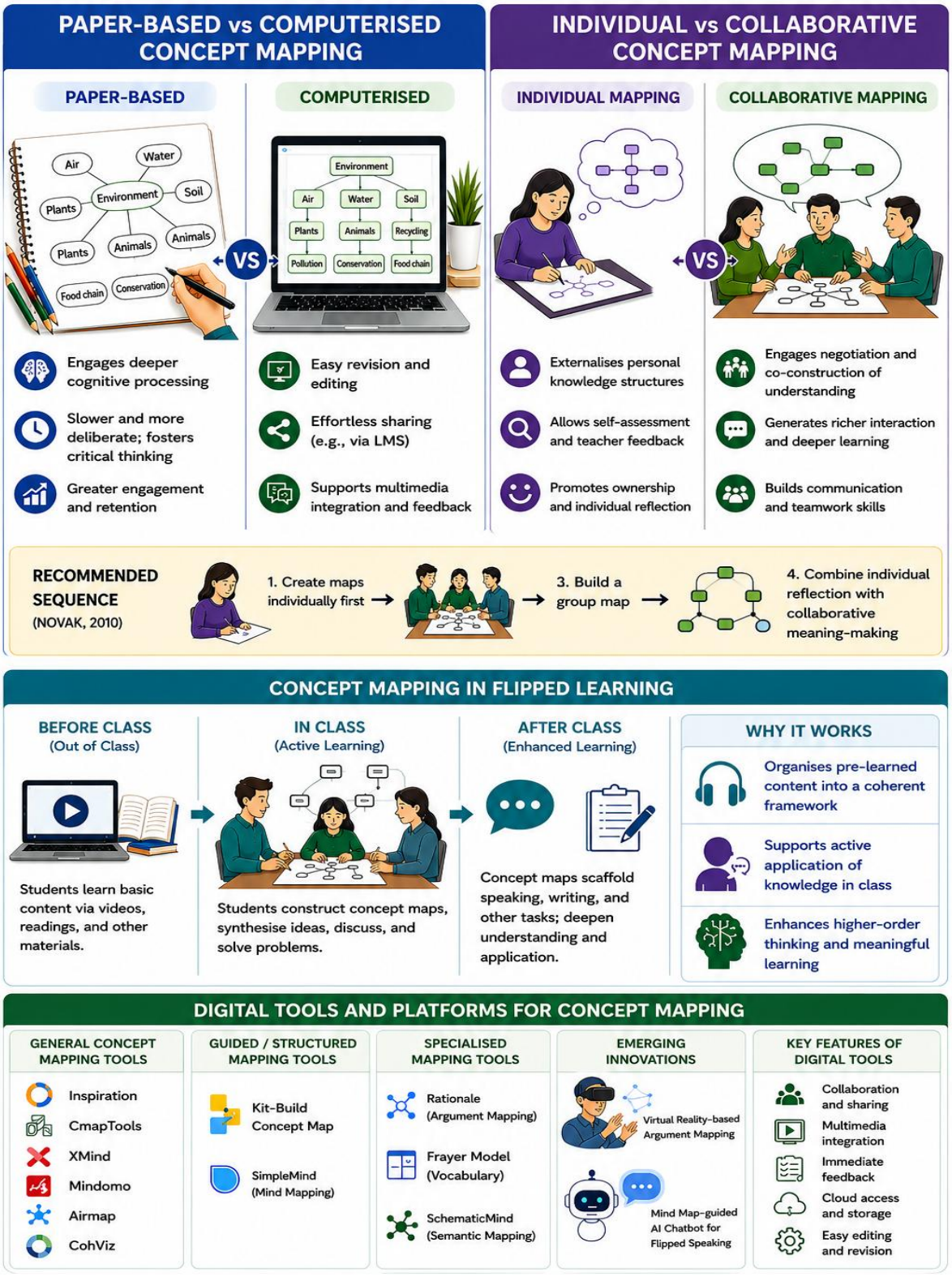

Figure 3. Instructional formats and technology integration in concept mapping

5. Effects on Language Achievement

5.1 Meta-Analytic Evidence

A meta-analysis comprising 68 studies and 14,656 participants reported a large pooled effect of concept mapping and related mapping strategies on L2 learning outcomes (Hedges' g = 1.047; Han, 2025). Interpretation requires caution because heterogeneity was very high (I^2 = 98.98%), mapping techniques were sometimes grouped together, and educational levels varied. A synthesis of computerised mapping studies also described frequent positive language and learner-perception findings, alongside null or mixed results (Li & Li, 2025). These results support concept mapping as a promising language-learning strategy, but do not directly establish effects on psychological well-being or clinical mental health. School-age achievement data from other subjects provide developmental context: a meta-analysis of 55 science-education studies involving pupils in Grades 3–12 reported a moderate pooled achievement effect (g = 0.776; Anastasiou et al., 2024). That estimate should not be treated as ESL/EFL-specific.

5.2 Writing Skills

Concept mapping is widely used as a pre-writing or organisational strategy, although findings depend on task design and learner characteristics. For example, Liu (2011) found that computer-based concept mapping significantly improved the writing quality of low- and intermediate-level ESL students. In a study of 94 college freshmen, both individual and cooperative mapping treatments boosted writing performance relative to no-mapping controls; higher-quality concept maps (especially those constructed collaboratively) predicted stronger final essays. Hassanzadeh et al. (2021) similarly reported that EFL learners using computer-aided concept maps in process writing produced essays with significantly higher lexical diversity than controls. In other words, mapping helped students generate and organise a wider range of vocabulary. Automated mapping-feedback tools have also yielded gains. Lachner et al. (2018) developed an online concept-map feedback system (CohViz) and showed that accurate map feedback during revision led to measurably more cohesive written explanations (medium effect sizes). Collaborative mapping before writing has comparable benefits; for example, Lee (2013) observed that Korean EFL learners who constructed concept maps together negotiated ideas more fully and wrote higher-quality essays. Collectively, these studies suggest that integrating concept mapping into the writing process enhances organisation, content richness, and coherence in L2 writing.

5.3 Reading Comprehension

Concept mapping can support L2 reading comprehension by making relationships within a text explicit. Pinandito et al. (2021) reported stronger reading performance and more focused discussion when EFL learners used a guided collaborative Kit-Build interface. Furtado et al. (2019) investigated a closed-map interface designed to reduce cognitive load, demonstrating that task demands and delayed retention do not necessarily change in the same direction; lower load should not be assumed to improve longer-term recall. Rassaei (2019) similarly showed that guided mapping and map correction can support comprehension and strategy awareness. These studies address comprehension and learning processes, not direct mental health outcomes; transfer to younger learners needs evaluation.

5.4 Vocabulary Development

Graphic organisers (semantic maps) are particularly effective for vocabulary learning. Bahr & Dansereau (2001) showed that bilingual concept maps significantly improved foreign-language word recall. Students using bilingual maps outperformed those using word lists on immediate and delayed vocabulary tests. By contrast, Khoii & Sharififar (2013) found no significant difference between semantic mapping and rote memorisation groups; both improved, but semantic mapping did not yield reliably larger gains. More recent mobile-assisted studies are more favourable; Shi & Tsai (2024) demonstrated that a mind-mapping mobile app significantly boosted EFL learners' vocabulary knowledge, with effects persisting at a delayed post-test. Similarly, Kaveh et al. (2023) compared mobile vs. paper concept mapping for 90 Iranian EFL learners and found that mobile concept mapping far outperformed both paper mapping and a no-mapping control on post-test and delayed vocabulary measures. Liu (2016) reported that EFL learners using a mobile concept-mapping strategy in a vocabulary course significantly outperformed a text-only control on both acquisition and retention of new words. Across studies, computerised or mobile concept mapping has repeatedly shown advantages for learning and retaining L2 vocabulary.

5.5 Speaking and Listening

Speaking and listening have received less attention than reading and writing. In a quasi-experimental university EFL study, Chen and Hwang (2020) reported better speaking performance, higher critical-thinking awareness, and lower

task-related speaking anxiety in a concept-mapping-supported flipped condition than in a conventional flipped condition. Wang and Liao (2014) and Alhomaidan (2015) also described improvements in oral communication among tertiary learners. These findings suggest that visual preparation can support language production; however, school-age psychological effects cannot be inferred directly from adult participants.

Evidence for listening is comparatively limited. Chen and Hwang (2020) reported better listening performance in their tertiary flipped-learning comparison, while broader reviews describe emerging applications of guided and computerised maps to listening tasks (Li & Li, 2025). It remains unclear whether the cognitive demands of listening and mapping interact differently in primary, secondary, and tertiary classrooms. Controlled studies that assess language comprehension alongside cognitive load and anxiety are needed before developmental recommendations can be made with confidence.

6. Effects on Reading Comprehension: A Focused Analysis

For school-age language learners, reading comprehension is both an educational outcome and a potential source of confidence or frustration. Concept maps can be used to preview text structure, record relationships during reading, and consolidate ideas afterwards. Han (2025) reported a large pooled effect for receptive skills, which combined reading and listening outcomes rather than isolating reading comprehension. Evidence should therefore be interpreted at the relevant skill and age level. Table 2 presents selected studies; most are not primary-school investigations.

6.1 Pre-Reading Applications

Concept mapping, used as a pre-reading strategy, serves as an advance organiser that activates learners' existing schemata, thereby reducing cognitive load during reading. By visually previewing main concepts and their connections, maps provide students with a framework for incoming information. Tajeddin and Tabatabaei (2016) found that Iranian high-school EFL students who brainstormed and constructed concept maps before reading significantly outperformed a control group in comprehension and recall; the maps "facilitate top-down interactions between the reader and the text". This aligns with theory (Ausubel's meaningful learning) that linking new content to prior knowledge eases learning. Early work by Kalhor and Shakibaei (2012) similarly reported that explicit concept-mapping instruction in high-school EFL classes led to significantly higher post-test reading scores ($t=3.388$, $p=0.002$). Thus, pre-reading mapping consistently boosts comprehension by priming relevant vocabulary and structures.

6.2 During-Reading and Post-Reading Applications

During reading, structured maps may direct attention to central ideas and reduce unnecessary search, but the map-building activity also consumes mental resources. Furtado et al. (2019) found that an interface intended to lower cognitive load did not improve immediate comprehension and was associated with poorer delayed retention in the comparison reported in Table 2. This finding illustrates a possible tension between ease of map construction and the deeper processing needed for durable learning. For children, partial maps, worked examples, and gradual removal of support warrant direct testing rather than automatic adoption.

After reading, having students create or complete a concept map consolidates the text's structure and supports review. Rassaei (2019) found that both guided map construction and map correction, in which students corrected an expert-generated map, significantly improved L2 learners' reading comprehension compared with the control group, with map correction producing the largest gains. Notably, the study also reported that concept mapping enhanced learners' metacognitive awareness of other reading strategies. In practice, post-reading mapping not only reinforces content organisation but also encourages learners to reflect on their reading processes. Thus, concept mapping during or after reading can improve the organisation and retention of textual information while promoting greater awareness and use of effective reading strategies.

6.3 Computerised Concept Mapping for Reading

Digital concept-mapping tools (CCMLL) have been widely used in EFL reading. Liu et al. (2010) found that a computer-assisted mapping strategy significantly improved EFL college students' reading comprehension and retention compared with conventional study methods. Collaborative digital platforms such as the Kit-Build system have also shown promise. In an online experiment, Pinandito et al. (2021) reported that pairs of EFL learners using the collaborative Kit-Build

mapping activity achieved significantly higher post-test reading scores than those creating freehand maps; the Kit-Build group also engaged in more on-topic discussion. This suggests that breaking map construction into guided steps (as in Kit-Build) can make the task more accessible and conversation-rich.

Argument mapping is another CCMLL approach. Eftekhari and Sotoudehnama (2018) showed that computer-assisted argument mapping helped learners retrieve key information from texts more effectively, thereby improving comprehension. However, not all CCMLL studies report uniform gains. Hwang et al. (2019) warned that the initial time and cognitive effort required to build digital maps can hinder reading progress if learners are not well trained. They observed that some students "took too long" to construct maps and failed to recognise the text's structure, yielding no comprehension benefit. Similarly, Furtado et al. (2019) found that without sufficient support (e.g., worked examples), learners may not fully benefit from mapping during reading. Thus, while computerised mapping can enhance reading outcomes, it often requires scaffolding (partial maps, templates, or collaborative guidance) to realise its full potential.

6.4 Effect Size Evidence

Han (2025) reported an overall L2 effect of g = 1.047 (95% CI [0.996, 1.098]) across 68 studies and larger effects for productive than receptive language skills (g = 1.576 versus 1.130). The receptive-skills estimate pools reading with listening; it must not be presented as a reading-only effect size. In addition, the extreme between-study heterogeneity restricts generalisation to specific school-age groups. Findings from individual reading studies remain important for interpreting instructional design and the relative contributions of attention, memory, and guided practice.

6.5 Pedagogical Implications

Teachers should consider integrating concept mapping at multiple stages of reading instruction. Pre-reading maps can activate background knowledge, during-reading maps can guide focused reading, and post-reading maps can reinforce structure and vocabulary. Computerised tools (e.g., Kit-Build or closed-mapping apps) offer additional support, particularly in collaborative settings, but require careful modelling. Instructors should allocate sufficient time for learners to master mapping tools and may need to provide partial maps or templates initially. Given the consistently large effect sizes, concept mapping is a promising strategy for EFL/ESL reading programmes, yet its success hinges on proper training and alignment with reading goals.

Table 2. Key studies on concept mapping and reading comprehension in ESL/EFL contexts

S. No.	Participants (n, proficiency)	Design	Map type	Outcome measures	Key findings	Effect Size (g/d)	Reference
1.	EFL college students (≈50)	Quasi-exp	Computerised (cooperative)	Reading comprehension test; retention quiz	Computer-assisted mapping significantly improved reading comprehension and retention (especially for weaker readers).	NA	Liu et al., 2010
2.	Adult EFL learners (≈60)	Experimental (pre/post)	Digital (argument map)	Recall and comprehension tests	Computer-assisted argument mapping enabled more effective retrieval of key text information, enhancing comprehension.	NA	Eftekhari & Sotoudehnama, 2018
3.	Iranian HS students (n=38, female)	Quasi-exp (pre/post)	Paper	RC test (analysis questions)	Concept-mapping instruction led to significantly higher post-test	NA	Kalhor & Shakibaei, 2012

					comprehension (t=3.388, p=0.002).		
4.	Iranian tertiary learners (n≈60)	Experimental	Paper	RC test; strategy awareness questionnaire	Guided mapping and map correction both outperformed the control; correcting an expert map yielded the largest gains; mapping also increased metacognitive strategy use.	NA	Rassaei, 2019
5.	Iranian HS students (n=60)	Experimental (map vs. control)	Paper	RC test; recall task	Learners who brainstormed and mapped concepts pre-reading significantly outperformed controls on comprehension and recall.	NA	Tajeddin & Tabatabaei, 2016
6.	Filipino undergraduates (n=40)	Quasi-exp (map vs. summary)	Paper	RC test	Concept-map group scored higher on comprehension than the summarisation group.	NA	Lumontad et al., 2020
7.	Iranian advanced EFL (n≈70)	Quasi-exp (pre/post)	Paper	RC test	Mapping instruction improved comprehension for both genders, with females benefiting more.	NA	Khaghaninejad & Arefinejad, 2015
8.	Indonesian senior HS (n≈100)	Quasi-exp	Digital (Kit-Build with review)	RC test	Kit-Build mapping (with source-connection) group significantly outperformed a summarisation control on a reading test.	NA	Andoko et al., 2020
9.	Indonesian EFL (n=20)	Experimental	Digital (Kit-Build, collaborative)	RC test; discourse analysis	Guided Kit-Build group achieved significantly higher comprehension scores than a freehand-mapping group (p≈0.001); Kit-Build students also engaged in	d≈1.93 (g≈1.85)	Pinandito et al., 2021

					richer on-topic discussion.		
10.	Japanese EFL (N=60)	Experimental (delayed test)	Digital (closed Airmap)	RC test (immediate and 2-week delayed)	A closed-map interface (lower cognitive load) produced no immediate comprehension benefit but significantly poorer retention after two weeks, indicating a trade-off between cognitive load and long-term retention.	NA	Furtado et al., 2019

Note: All studies were peer-reviewed experiments in ESL/EFL contexts. Effect sizes are reported as Hedges' g or Cohen's d where available. "NA" indicates that no effect size was reported or could be calculated from the source.

7. Psychological and Affective Dimensions of Concept Mapping

7.1 Learner Attitudes and Classroom Experience

Learner perceptions shape engagement with visual learning activities, although positive attitudes do not necessarily imply reduced psychological distress. Li and Li (2025) observed that relatively few computerised language-mapping studies directly assessed motivation, cognitive load, or broader learner perceptions. Studies of collaborative digital writing and mapping tools reported favourable views of usability and classroom participation (Kilickaya, 2020; Shi & Tsai, 2024). In school-age settings, usability should be assessed in relation to reading ability, developmental level, digital access, and perceived task difficulty. A K–12 review found that concept maps were frequently used as individual and collaborative learning tools, whereas anxiety was rarely a primary outcome (Chang et al., 2022).

7.2 Language-Learning Anxiety and Psychological Safety

The most directly relevant affective outcome is language-learning or speaking anxiety, rather than a clinically diagnosed anxiety disorder. In a tertiary EFL study, Chen and Hwang (2020) found lower post-intervention speaking-anxiety scores with concept-mapping-supported flipped learning (adjusted mean approximately 2.45 versus 3.07; $F = 30.23$, $p < .01$). Yet evidence from younger learners is not uniformly positive. A junior-high study comparing concept-mapping-supported spherical-video virtual-reality speaking tasks with conventional tasks found no statistically significant between-group differences in speaking anxiety or self-efficacy (Hwang et al., 2026). These divergent findings indicate that classroom anxiety may depend on age, language proficiency, teaching environment, technology demands, and the anxiety instrument employed. Neither study establishes a treatment effect on clinical childhood anxiety.

7.3 Critical Thinking and Metacognitive Awareness

Concept mapping requires learners to select concepts, explain relationships, assess gaps, and revise an emerging representation. Chen and Hwang (2020) reported higher critical-thinking awareness in their tertiary EFL mapping condition, while Rassaei (2019) found improvements in reading-strategy awareness. Evidence from junior-high learners is particularly pertinent: Lenski et al. (2022) reported benefits of map-construction training for learning performance, map quality, and aspects of self-evaluation. Such findings support a plausible role in metacognitive monitoring, but map quality alone should not be treated as a validated measure of broader cognitive development or emotional adjustment.

7.4 Motivation and Engagement

Motivation and engagement are important educational-psychology outcomes because interest, persistence, and willingness to participate can affect language practice. Lan et al. (2015) reported favourable writing-motivation outcomes in primary-school EFL cooperative prewriting that included mind mapping; this evidence should not be attributed exclusively to Novakian concept maps. Digital concept-mapping and related mapping studies with older

learners also report positive engagement or attitudes (Hsu, 2019; Liu, 2016; Li & Li, 2025). Nevertheless, intervention novelty, teacher attention, group cooperation, and assessment expectations may contribute to apparent motivational gains. Child-specific studies should distinguish intrinsic motivation from momentary enjoyment and report validated measures.

7.5 Academic Self-Efficacy and Confidence

Self-efficacy refers to an individual's perceived capability to achieve a particular task, not to global psychological well-being (Bandura, 1997). In an EFL reading context, Khajavi and Ketabi (2012) reported higher reading self-efficacy following concept-mapping instruction. Visualising relationships and recognising progress may help learners plan answers and approach challenging language tasks with greater confidence; however, these are proposed pathways, not universal effects. Importantly, Hwang et al. (2026) found no significant improvement in self-efficacy in their junior-high speaking-task comparison. Confidence claims should therefore specify the task, participant age, measurement instrument, and strength of evidence.

7.6 Cognitive Load, Working Memory, and Self-Regulated Learning

Concept mapping can support comprehension by externalising relationships that would otherwise have to be maintained in working memory. At the same time, deciding which concepts to include, arranging a hierarchy, and labelling cross-links may increase cognitive demands, particularly for novice or younger learners (Sweller, 1988; Furtado et al., 2019). A university study of load-reduction instruction reported lower intrinsic and extraneous load and higher map quality after targeted training (Li et al., 2025), but this result should not be assumed to apply to children. Practical adaptations include modelling a short map, supplying a partially completed structure, limiting the number of concepts initially, and allowing opportunities for revision. Such adaptations should be evaluated with both performance and child-appropriate cognitive-load measures.

7.7 Peer Relationships, Classroom Participation, and Social-Emotional Learning

Collaborative mapping requires students to explain links, negotiate meanings, compare perspectives, and revise shared representations. Studies of collaborative knowledge construction indicate benefits for elaborative discussion and peer interaction (van Boxtel et al., 2002; Pinandito et al., 2021). In school-age groups, these activities could provide opportunities to practise turn-taking, constructive disagreement, and help-seeking. However, group participation is not equivalent to improved peer relationships or social-emotional competence. Unequal contribution, public criticism, or competitive comparison may instead increase frustration or reluctance to speak. Studies should assess perceived belonging and psychological safety directly, rather than inferring them from collaboration alone.

7.8 Psychological Well-Being: Potential Relevance and Evidence Boundaries

Children's experiences of language learning encompass achievement, perceived competence, classroom participation, and emotional responses to evaluation. Concept mapping may indirectly support a more predictable and supportive learning experience by making task expectations visible and allowing preparatory reflection. The available literature, however, largely measures academic performance, speaking anxiety, motivation, or self-efficacy; evidence directly linking concept mapping to validated measures of children's overall psychological well-being remains insufficient. Learning-related anxiety is context-specific and should not be equated with generalised anxiety disorder, depression, or other psychiatric outcomes. Concept mapping should therefore be considered a potentially supportive pedagogical practice—not a mental health intervention. Future trials should measure educational and psychological outcomes separately and include appropriate safeguarding and referral pathways where clinically significant difficulties are identified.

Table 3. Evidence and limitations for psychological outcomes of mapping approaches in language education

Domain	Reported pattern	Interpretation and evidence gap	Illustrative evidence/population
Learning anxiety	Lower speaking anxiety in tertiary mapping intervention; no significant difference in junior-high comparison	Classroom-specific measures; do not generalise to clinical anxiety	Chen & Hwang, 2020; tertiary EFL; Hwang et al., 2026; junior high EFL

Academic self-efficacy	A positive reading-related finding; null junior-high speaking self-efficacy finding	Effects vary by task, population, and instrument	Khajavi & Ketabi, 2012; EFL reading; Hwang et al., 2026; junior high
Motivation / engagement	Favourable motivation/engagement reports in several studies	Lan intervention used mind mapping; do not attribute to concept mapping alone	Lan et al., 2015; primary EFL; Li & Li, 2025; mixed educational levels
Metacognition	Map-construction training assisted learning and self-evaluation; some reading-strategy gains	Limited evidence that these transfer to broader psychological development	Lenski et al., 2022; junior high; Rassaei, 2019; L2 learners
Cognitive load	Interface design and instruction change task load; reduced load does not always improve retention	Developmentally appropriate task complexity and guidance need testing	Furtado et al., 2019; Li et al., 2025; tertiary/university
Peer interaction	More elaboration and on-task discussion in collaborative mapping activities	Peer belonging and emotional safety seldom measured directly	van Boxtel et al., 2002; Pinandito et al., 2021; mixed learning contexts
Overall mental well-being	No established clinical or global child well-being benefit	Requires validated age-appropriate mental health/well-being endpoints	Concept-mapping ESL/EFL studies reviewed here

Note: Evidence is illustrative, not a quantitative synthesis of psychological outcomes. Study settings and instruments differ, and studies using mind maps or combined technology interventions are identified separately.

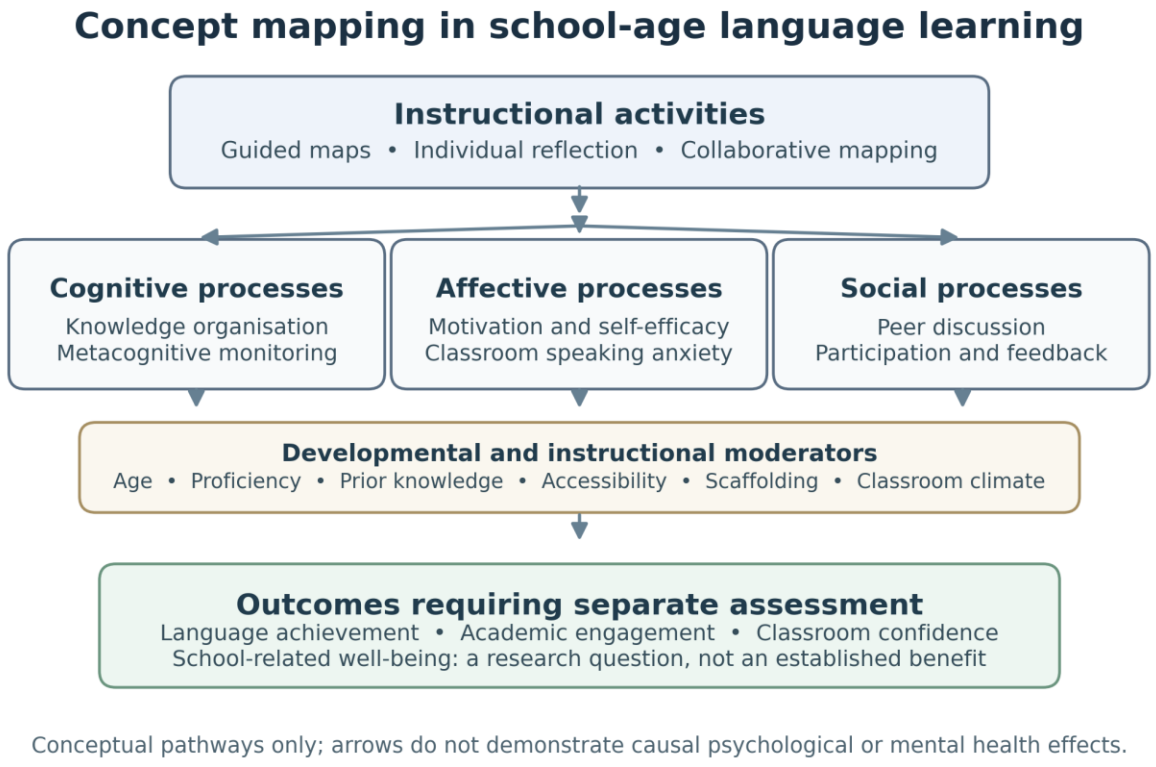

Figure 4. Proposed cognitive, affective, and social pathways connecting classroom concept mapping with school-age language learning. This framework is conceptual. The hypothesised pathways and psychological well-being outcomes are not established causal effects.

8. Moderating Variables

The magnitude and nature of concept-mapping effects vary substantially across populations and tasks. In Han's (2025) L2 meta-analysis, heterogeneity was very high (I^2 = 98.98%), indicating that a single overall effect should not be used to predict outcomes in a particular child's classroom. Developmental stage, previous mapping experience, language proficiency, task difficulty, accessibility, teacher feedback, and classroom climate are all relevant candidate moderators. Most of these have not been tested systematically for psychological outcomes.

8.1 Educational Level and Learning Context

Han (2025) reported larger mean L2 effects in language institutes (g = 1.551), secondary settings (g = 1.401), and tertiary settings (g = 1.143), with smaller effects in primary education (g = 0.475) and graduate settings (g = 0.632). These estimates describe language achievement, not mental health or cognitive development, and the underlying studies differ in many respects. School-age evidence from other subjects also supports attention to grade and teacher guidance: Anastasiou et al. (2024) found an overall science-achievement benefit for Grades 3–12, with variability by grade and learning circumstances. Age-related readiness is a possible explanation that requires direct experimental testing rather than an established mechanism.

8.2 Target Language and Geographic Region

Concept mapping showed a positive effect on English as a second/foreign language (g = 0.752) but a negative effect for non-English L2 learners (g = –1.158). Studies in the Middle East (g = 1.484) and Europe (g = 1.012) reported stronger effects than those in East Asia (g = 0.826) and South Asia (g = 0.308). By contrast, North American studies showed non-significant effects (g = 0.449, p = .303). The L1–L2 linguistic distance and the typological relationship between learners' first and target languages appear to be key explanatory factors, as concept mapping may better facilitate vocabulary and conceptual connections when the L1–L2 distance is greater (Han, 2025).

8.3 Mapping Format

Across studies in Han's (2025) synthesis, paper-based mapping yielded a larger mean L2 effect than computerised mapping (g = 1.499 versus 0.892), although these are comparisons across heterogeneous interventions. Differences in task, training, access to devices, and age may influence outcomes. Simple paper maps may reduce technical barriers for some children, whereas accessible digital maps may facilitate correction, sharing, and structured feedback. Neither format has been shown to be psychologically superior for school-age learners.

8.4 Individual vs. Cooperative Format

Collaborative mapping can promote negotiation, explanation, and peer support (van Boxtel et al., 2002), but collaborative versus individual effect sizes in Han (2025) did not differ significantly in the overall subgroup test (p = .052). In children and adolescents, participation should be supported through balanced roles and nonjudgmental feedback. Academic performance, perceived belonging, and psychological safety should be assessed separately instead of treating collaborative work as evidence of improved social-emotional well-being.

8.5 Duration of Instruction

In a meta-analysis (Han, 2025), regression analysis confirmed that the duration of concept mapping instruction was a significant positive moderator (β = 0.047, p = .023). Longer concept mapping interventions yielded progressively stronger effects on L2 learning. This finding aligns with skill acquisition theory (DeKeyser, 2007), which emphasises that automatization of organised knowledge representation, as supported by concept mapping, requires sustained practice over time.

8.6 Productive vs. Receptive Skills

Concept mapping demonstrated larger effects on productive skills (g = 1.576) than on receptive skills (g = 1.130). The stronger effects on productive skills (writing and speaking) can be explained by the explicit scaffolding that concept maps provide for organising output, reducing the cognitive demands of real-time production, and enabling learners to channel cognitive resources towards linguistic accuracy and communicative complexity (Han, 2025).

9. Challenges and Limitations

Concept mapping entails challenges relevant to both learning and classroom emotional experience. Time demands, weak scaffolding, digital barriers, and unfamiliar mapping conventions can create frustration or cognitive overload (Hwang et al., 2019; Li & Li, 2025). Children may need explicit modelling, smaller concept sets, concrete vocabulary, accessible formats, and gradual movement from guided to independent mapping. Teachers should avoid using map quality as a proxy for intelligence, mental health, or motivation. Publicly comparing maps or assigning unstructured group work may disadvantage learners with different language proficiency, communication preferences, or support needs. Age-appropriate, inclusive implementation is therefore central to both educational quality and a supportive classroom climate.

The evidence base also has methodological limitations. Han (2025) reported extreme heterogeneity and combined educational contexts and mapping variants. Many affective studies focus on adults, and some interventions include additional components, such as flipped instruction, collaboration, and virtual reality, making the isolated contribution of concept mapping uncertain. Anxiety and confidence findings are mixed, with a null junior-high result contrasting with a positive tertiary result (Chen & Hwang, 2020; Hwang et al., 2026). Outcomes such as classroom enjoyment and speaking anxiety do not establish changes in clinical mental health. Future studies should report age, baseline proficiency and anxiety, mapping type, intervention fidelity, comparison activity, validated child-appropriate instruments, and adverse or frustrating learning experiences.

10. Implications and Future Directions

Concept mapping may be incorporated progressively in ESL/EFL teaching, beginning with worked examples and partially completed maps before independent or collaborative construction. For school-age learners, the strategy should match developmental stage, language proficiency, accessibility needs, and classroom expectations. Teachers may use individual maps for self-monitoring and small-group maps for discussion while maintaining psychological safety through specific feedback and noncompetitive assessment. Programmes should assess language outcomes, task-specific confidence, motivation, and cognitive load separately. When children experience substantial anxiety or distress, pedagogical adjustments may be helpful but do not replace assessment or support by appropriately qualified professionals.

Future research should test age-appropriate hypotheses about psychological mechanisms rather than infer general well-being benefits from academic improvements. Priority designs include controlled school-based studies with preregistered outcomes, active instructional comparators, delayed follow-up, fidelity checks, and stratification by age and baseline proficiency. Studies should use validated measures of foreign-language anxiety, academic self-efficacy, motivation, cognitive load, and—in a distinct exploratory domain—school-related psychological well-being. Teacher guidance, map complexity, individual versus cooperative formats, and paper versus digital tools are important moderators. Qualitative interviews may help identify frustration, perceived control, peer dynamics, and students' preferences. AI-supported mapping should be evaluated for usability, privacy, bias, and the risk of over-reliance, especially when deployed with minors.

11. Conclusion

Concept mapping provides a structured way to relate concepts, organise language knowledge, and support reading, writing, and oral communication. Meta-analytic findings favour language achievement, but effects differ greatly among settings and are smaller on average in primary than secondary education (Han, 2025). Psychological outcomes deserve separate consideration: motivation, self-efficacy, metacognitive awareness, and classroom speaking anxiety may be influenced by mapping, yet direct school-age findings are limited and sometimes null. Complex tasks may also produce frustration or excess cognitive load. Developmentally appropriate scaffolding, accessible materials, constructive feedback, and supportive peer interaction are therefore important. The current evidence justifies investigation of school-related psychological well-being, not a claim that concept mapping prevents or treats mental health disorders. Rigorous child- and adolescent-focused studies are needed to determine whether, for whom, and under what conditions cognitive and affective benefits emerge.

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The authors declare that generative AI and language-support tools assisted in manuscript preparation. Paperpal (Cactus Communications), Grammarly and ChatGPT (OpenAI) were used for language editing and editorial revision, and Claude (Anthropic) assisted figure development. The authors reviewed the AI-assisted material and take responsibility for the final text, figures and interpretations.

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