

Structured External Representations

Object-Oriented Thinking (OOT) Beyond Its Own Literature. A Systematic Literature Review

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ABSTRACT: External representations are ubiquitous in knowledge work, yet the literature explaining how they support thinking remains fragmented across disciplines, representational forms, and theoretical traditions. This systematic literature review examined three observable domains of the emerging concept of Object-Oriented Thinking (OOT): verbal, visual, and tangible external representations in which mental models, information, and organization are explicitly instantiated. Literature was identified through three complementary discovery domains and subjected to abstract screening, cross-domain characterization, accessibility assessment, and systematic analysis, yielding a validated synthesis corpus of 51 publications. The synthesis identified seven interrelated themes: structured externalization of knowledge; representations as reasoning environments; iterative sensemaking and knowledge construction; human–technology complementarity in knowledge systems; shared representations and distributed knowledge work; embodied and material engagement with representations; and persistent, traceable, and reusable knowledge. Four cross-cutting principles qualified these processes: representational fit and alignment; scaffolding, facilitation, and representational competence; domain and contextual knowledge; and representational integration and coherence. Across the corpus, a consistent pattern emerged: externalization alone was not the central contribution. External representations became consequential when information and relationships were organized into structures that could be inspected, manipulated, reasoned with, revised, coordinated, and preserved. Their effects varied with representational structure, task, user, context, and integration. The evidence base was conceptually convergent but methodologically heterogeneous and unevenly distributed across disciplines and representational forms, limiting stronger causal and comparative inference. The review does not establish OOT as a validated theoretical construct. It does, however, show that the phenomena encompassed by its operational definition are supported by a substantial and interconnected literature. By integrating that literature, the review provides an evidence-based account of structured external representation and a foundation for investigating more precisely *what is made explicit, how it is organized, and what value arises from making thought externally available for continued knowledge activity.*

KEYWORDS: Object-Oriented Thinking | structured external representation | external cognition | knowledge representation | sensemaking | distributed cognition | human–technology complementarity | systematic literature review

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1. Introduction

1.1 Background and Conceptual Context

Humans routinely externalize thought through language, diagrams, models, physical artifacts, and other representational forms to support reasoning, communication, learning, and problem solving. Across numerous disciplines, these external representations have been investigated from different theoretical and methodological perspectives, often with an emphasis on particular representational modalities or domain-specific applications. Collectively, this body of work reflects sustained scholarly interest in how representations support thinking, yet it has not traditionally been examined within a single unifying conceptual framework. [1–4]

This manuscript reports a systematic literature review motivated by the emerging concept of Object-Oriented Thinking (OOT)—a comparatively recent construct with an older theoretical [5–12] and explanatory[13–25] lineage. For close to two decades, research on DSRP Theory, systems mapping, tactile manipulatives, visual mapping, structural cognition, and model-world alignment has addressed a common practical question: how can the organization of thought be moved out of the mind and into an external form that can be seen, touched, examined, revised, shared, and tested?

That work began in practice before OOT was articulated as a formal construct. DSRP described thinking as the active organization of information through Distinctions, Systems, Relationships, and Perspectives. *Thinking at Every Desk* [26], ThinkBlocks [15,27,28], work on tactile cognition [13], and subsequent systems-mapping research [29] progressively externalized that structure onto paper, whiteboards, physical objects, and software. The practical principle was straightforward: when a problem becomes too complex to manage comfortably in working memory, externalize the thinking into a form that can itself be manipulated.

The systems-mapping literature later made the object-oriented character of this approach more explicit. Castellanos Canales, Lucio Maymon, and Cabrera characterized effective systems mapping as visual, tactile, object-oriented, social, and embodied [30]. More importantly, they explained why these characteristics matter. When ideas become sufficiently difficult or complex, cognition can be externalized so that thought occupies a physically or visually manipulable space. The particular medium may vary—a napkin, whiteboard, blocks, Post-it notes, or software—but the underlying requirement remains the same: the external representation must have enough cognitive architecture to preserve and carry the organization of the mental model.

Externalization is not a definitional requirement of OOT. OOT concerns the explicit instantiation of the organization of thought in object-like forms that can be inspected or manipulated; such instantiation may

occur internally, as in mentally visualized objects, or externally through diagrams, physical objects, language, software, and other representational media. Because externally instantiated forms are observable, persistent, and recoverable in the scientific literature, this review deliberately examines the external case. External representation therefore defines the evidentiary scope of this review, not the conceptual boundary of OOT.

1.2 Problem Statement

Research concerning external representations spans numerous disciplines, including education, cognitive science, psychology, computer science, engineering, design, and information visualization. Although these fields have generated substantial knowledge about how representations support thinking, they have generally done so using discipline-specific terminology, theoretical perspectives, and representational emphases. Consequently, knowledge relevant to the broader phenomenon of externalized thinking remains fragmented across multiple literatures that are seldom synthesized within a common conceptual framework.[1–4]

This fragmentation makes it difficult to determine what is collectively known, where findings converge, where important disagreements or uncertainties remain, and how different representational modalities relate to one another. Without an integrated synthesis, researchers and practitioners lack a comprehensive account of the current state of knowledge concerning these representational phenomena.

Accordingly, a systematic literature review was needed to synthesize the existing evidence, establish the current state of knowledge, and provide an empirical foundation for future theoretical and empirical development.

1.3 Review Purpose and Rationale

Building on the operational framing introduced above, the purpose of this review was to establish the current state of knowledge concerning the representational phenomena encompassed by the project's operational scope for examining Object-Oriented Thinking (OOT). Rather than evaluating the literature according to established DSRP or OOT terminology, we used terminology established in the broader literature to identify, organize, and synthesize research examining verbal, visual, and tangible forms of external representation.

The review was conducted using the Systems Literature Review (SLR) Protocol for Humans Supported by AI [31], developed by Drs. Derek and Laura Cabrera. The governing protocol provides a structured methodology for systematically identifying, analyzing, synthesizing, and reporting the condition of knowledge within a research domain while allowing individual reviewers to make project-specific operational decisions appropriate to their research questions and conceptual boundaries. Within this framework, we implemented a structured search, analysis, and synthesis process tailored to the representational phenomena examined in this study. [32,33]

By applying this methodology, we sought to transform a diverse and fragmented body of literature into a transparent, evidence-based synthesis of the current state of knowledge and to provide a rigorous foundation for subsequent theoretical refinement and empirical investigation.

1.4 Research Question

The review was guided by the following research question:

What is the current state of knowledge regarding verbal, visual, and tangible external representations in which mental models, information, and organization are explicitly instantiated, as an observable domain relevant to Object-Oriented Thinking (OOT)?

To address this question, we systematically identified, analyzed, and synthesized research across the three operational representational domains established for the study. The objective was not to determine the characteristics of OOT from within its own literature base, but to evaluate the extent and character of the broader body of knowledge concerning the representational phenomena encompassed by its operational definition.

2. Methods

2.1 Systematic Literature Review Protocol

This manuscript reports a systematic literature review conducted using the Systems Literature Review (SLR) Protocol for Humans Supported by AI [31]. The protocol organizes the review process into five phases: *preparation*, which establishes the review process and parameters; *search*, which gathers relevant literature; *analysis*, which extracts, summarizes, and categorizes findings; *synthesis*, which identifies patterns, gaps, and trends across the literature; and *writing*, which integrates the findings into a cohesive manuscript. Its purpose is to transform traditional narrative literature reviews into transparent, systematic, and empirically grounded investigations through reproducible methodological procedures [32,33].

Review-specific implementation decisions and methodological refinements were documented in a structured researcher journal, including the rationale for decisions and quality-control procedures.

AI assisted with defined tasks, including search-strategy refinement, abstract evaluation, structured literature extraction, and evidence synthesis, using prompts and decision rules established by the researcher. Methodological authority remained with the human reviewer, who evaluated AI outputs and resolved disagreements.

2.2 Search Strategy

Consistent with the governing SLR protocol, the review began with the development of a systematic search strategy. Because the review deliberately operated outside established OOT terminology, developing an effective search strategy required an iterative process of conceptual refinement before comprehensive literature retrieval could begin. Rather than adopting terminology from any single discipline, we first established provisional conceptual definitions for the major representational dimensions of OOT and then translated those concepts into established scientific vocabulary suitable for systematic searching.

Candidate search strings were pilot tested against retrieved abstracts, allowing both the search vocabulary and the operational boundaries of the emerging concept to be refined before full-scale literature collection.

The finalized search strategy organized the review around three complementary discovery domains corresponding to distinct modes of external representation: (1) visual representations, (2) physical or tangible representations, and (3) organizational or verbal structures.

2.3 Selection

Table 1 shows the number of records retained at each stage, from the initial search results through the final validated corpus of 51 publications.

Table 1. Sequential construction of the final synthesis corpus.

Step	Review Procedure	Started with	Ended with	Difference
1. Search-string development	Developed and tested search terms across three search domains: visual (V1), physical/tangible (V2), and organizational/verbal (V3). Tested candidate strings by reviewing the first 20 abstracts returned; retained five search strings per vector.	136,049	704	-135,345
2. Abstract screening	Applied the rule Step 1 AND (Step 2 OR Step 3): an explicit representation plus either a cognitive contribution or abstraction/generalizability.	704	310	-394
3. Cross-vector characterization	Asked whether each already-relevant paper also contained the complementary representational property needed to show represented information (I) + explicit organization (O). V1 – Visual (129); V2 – Physical/tangible (78); V3 – Organizational/verbal (103); V1→V3 (60); V2→V3 (38); V3→V1 (29); V3→V2 (1).	310	128	-182
4. Full-text accessibility	Attempted to retrieve the full text of all 128 cross-vector-relevant papers. Of these, 64 were accessible and 64 were inaccessible.	128	64	-64

5. Corpus validation	Removed duplicate or otherwise corrupted records from the accessible full-text corpus.	64	51	-13
6. Final synthesis corpus	Applied the standardized literature-extraction protocol to the validated publications used for all subsequent analysis and synthesis.	51	51	0

Table 1 summarizes the sequential construction of the final synthesis corpus. Search terms were developed by translating the emerging OOT concept into established scientific terminology and pilot testing candidate search strings for relevance and coverage. Retrieved abstracts were then screened independently within the three search domains using a common inclusion rule requiring an explicit representation together with evidence of either cognitive contribution or abstraction/generalizability. These criteria established the operational boundary of the review corpus by distinguishing representations that make information and organization explicit for knowledge activity from objects that merely result from human thought. Screening decisions were based on explicit evidence in the abstracts rather than inferred characteristics, with AI-assisted decisions subject to human review.

Papers meeting the initial relevance criteria were subsequently characterized for the complementary representational property needed to establish the combined presence of represented information and explicit organization. This cross-vector characterization was distinct from the initial screening: it evaluated already-relevant papers for the complementary property rather than reapplying the full inclusion criteria. Full-text accessibility was then assessed independently of relevance. Inaccessible publications remained documented as relevant at the abstract level but could not proceed to literature analysis. Finally, the accessible corpus was validated before the standardized literature-extraction process was applied to the 51 publications used for subsequent analysis and synthesis.

3. Analysis

3.1 Paper-Level Validation and Analysis

Once the review corpus was established, each of the 51 publications was analyzed individually using a standardized literature-extraction protocol. The resulting paper-level records captured bibliographic information, research objectives, methodology, principal findings, disciplinary and methodological classifications, empirical status, narrative summaries, and supporting evidence.

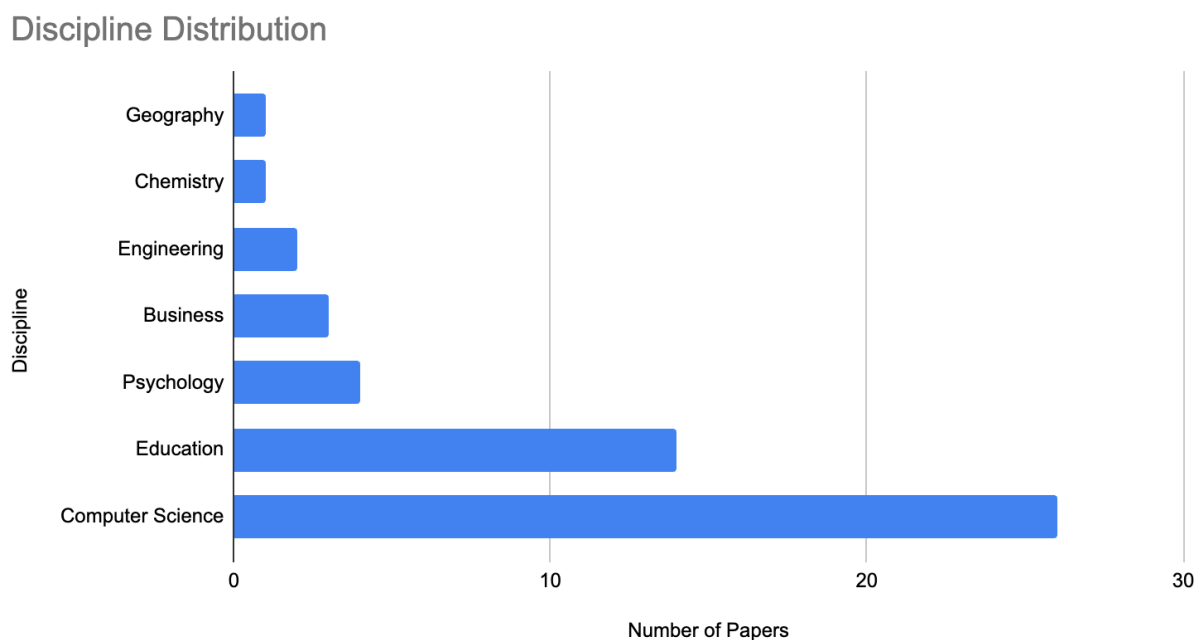
Analytical records were grounded in evidence extracted directly from each publication rather than reviewer inference, with supporting quotations and page numbers retained for traceability. AI applied the standardized extraction protocol, and the researcher verified the resulting records for accuracy, completeness, and consistency. The completed dataset was then audited, identified errors were corrected and reverified, and the validated records were frozen as the evidence base for subsequent analysis and synthesis.

The following analysis describes the characteristics and contributions of these publications at the individual-paper level. Cross-paper patterns, thematic relationships, and integrated interpretation are addressed separately in the synthesis.

3.2 Characteristics of the Analyzed Literature

The validated corpus spanned seven disciplinary categories (Figure 1).

Figure 1. Discipline Distribution

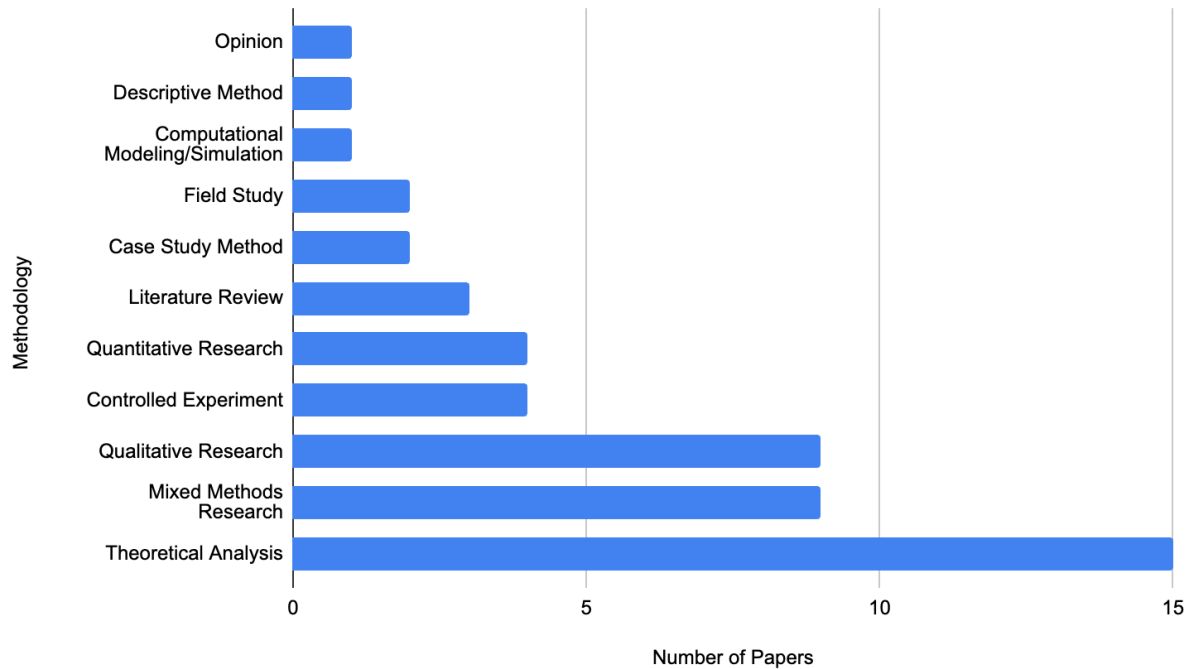


The disciplinary composition of the corpus was uneven. Computer Science represented the largest category (26 publications; 51.0%), followed by Education (14; 27.5%). Psychology contributed four publications (7.8%), Business three (5.9%), Engineering two (3.9%), and Chemistry and Geography one publication each (2.0% each). Together, Computer Science and Education accounted for more than three-quarters of the validated corpus.

The corpus also included a range of primary methodological approaches spanning empirical and nonempirical research (Figure 2).

Figure 2. Primary Methodology Distribution

Primary Methodology Distribution



Theoretical Analysis was the most frequent primary methodology (15 publications; 29.4%). Mixed Methods Research and Qualitative Research each accounted for nine publications (17.6%). Controlled Experiment and Quantitative Research each accounted for four publications (7.8%), followed by Literature Review (3; 5.9%), Case Study Method and Field Study (2 each; 3.9%), and Computational Modeling/Simulation, Descriptive Method, and Opinion (1 each; 2.0%).

Overall, 32 publications (62.7%) were classified as empirical and 19 (37.3%) as nonempirical.

3.3 Paper-Level Findings

The 51 publications examined external representation across a wide range of forms, purposes, and research contexts. The complete individual-paper analytical record, including all 10 analytical fields for each publication, is provided in the Appendix: Supplementary Table S1 – Analysis Paper-Level Records. The findings summarized here are drawn from those records, particularly the *What Did They Do?*, *What Does It Say?*, and narrative fields.

Across the individual papers, external representations were used to make information, ideas, relationships, reasoning processes, and knowledge structures available for examination or interaction. The forms studied included diagrams, maps, visualizations, semantic canvases, sketches, models, tangible interfaces, physical data representations, manipulatives, artifacts, and structured verbal or computational knowledge representations. Several papers examined representations that combined modalities, such as

speech with visual semantic organization, physical manipulation with visual information, or tangible artifacts with digitally encoded data.

A recurring finding at the paper level was that externalization could change how people worked with information rather than simply provide another way to display it. Individual studies reported that representations supported activities such as organizing and reorganizing ideas, identifying relationships, comparing alternatives, planning, interpreting information, and revising emerging understandings. For example, mind maps improved software-design quality in an experimental study; an AI-assisted semantic canvas supported organization, reflection, and iterative clarification of spoken thoughts; and diagrammatic representations supported unfamiliar probability reasoning by helping users identify subproblems, activate prior knowledge, and interpret instructions. Other papers similarly described external representations as resources that users could inspect, manipulate, revisit, or restructure during ongoing reasoning.

The individual studies also showed that the effects of representation depended on how information was structured and how users could interact with it. Simply making information visible or physical was not consistently sufficient. Studies of computer games, tangible interfaces, information visualization, and educational manipulatives reported differences associated with the form of the representation, the task, the available interaction, and the user's ability to understand or manipulate the representation. Direct manipulation of an externalized game structure, for example, supported planning more effectively than merely displaying that structure. Research on physical and tangible visualization likewise found advantages for some tasks while concluding that physicality itself was not inherently superior. Educational research similarly emphasized matching representational and interaction characteristics to particular learning purposes.

A number of papers examined external representations as part of iterative activity. Participants constructed, modified, compared, tested, or reworked representations as their understanding developed. Children creating data physicalizations evaluated and adjusted their representations while making them; pre-service teachers identified problems in geometry, scale, alignment, and measurement by moving between sketches, digital models, and physical prints; and users of tangible and material systems developed understanding through repeated cycles of construction and interaction. In these studies, the representation was not only an outcome of thought but also something that could provide information back to the person using or creating it.

The paper-level record also showed a social and collaborative dimension. Studies reported uses of external representations for communication, coordination, shared interpretation, teaching, collaborative problem solving, and the integration of knowledge distributed across people. Cognitive maps were described as a means of externalizing and organizing collective knowledge; service-design representations supported articulation, learning, collaboration, communication, and empathy; and enterprise models were described as distributing reasoning across people, representations, organizational processes, and computational technologies. Classroom research likewise found that conceptual learning was strengthened when teachers explicitly connected concepts, procedures, and multiple representations during discussion.

Physical and tangible representations added another set of findings. Papers examining data physicalization, tangible interaction, material representations of activity data, digital fabrication, and mathematical manipulatives reported that bodily action, spatial arrangement, touch, construction, and material properties could participate in the representational process. These studies associated physical engagement with spatial reasoning, reflection, exploration, motivation, communication, and sensemaking. At the same time, several explicitly cautioned against treating embodiment or tangibility as automatically beneficial. Effects depended on the relationship among the representation, physical action, task, user, and information being represented.

Several papers also addressed the persistence and history of externalized work. Representations could preserve intermediate reasoning, analytical provenance, prior decisions, or constructed knowledge so that these could be revisited. Work on intelligence analysis, for example, argued that representing provenance preserves the history of an analysis and supports reflection during sensemaking. Other studies described representations as records that could be retained, compared, communicated, reused, or incorporated into subsequent activity.

The corpus also contained important qualifications and counterpoints. Representations could introduce cognitive demands, require representational competence, constrain interpretation, or privilege some information and relationships over others. More representation was therefore not necessarily better representation. Individual papers identified trade-offs involving abstraction and specificity, stability and animation, precision and discreteness, physical and digital interaction, and the use of single versus multiple representations. Some studies found benefits only under particular task conditions, while others identified weaknesses in users' ability to construct, interpret, or coordinate representations effectively.

Taken together at the paper level, the literature did not describe external representations as passive containers for already-completed thought. Across otherwise diverse studies, the findings repeatedly documented cases in which making information or knowledge externally available allowed people to perceive, organize, manipulate, test, communicate, preserve, or reconsider aspects of that information. The specific effects varied substantially by representational form, task, context, and user interaction. These paper-level findings provide the descriptive analytical record from which the subsequent cross-paper synthesis was developed.

3.4 Framework Application

With the standardized analytical records established and verified, each of the 51 publications was systematically evaluated against the finalized analytical framework. Publications were assigned to one or more themes when their validated evidence showed substantive alignment with the corresponding theme definitions. Because the themes represented recurring patterns across the corpus rather than mutually exclusive categories, individual publications could support multiple themes. Publications were also evaluated for the four cross-cutting principles, which represented conditions influencing multiple representational processes rather than additional thematic categories.

Framework application did not introduce new evidence or modify the previously validated paper-level findings. Instead, it organized those findings within a common conceptual structure that enabled

consistent comparison across the corpus while preserving each publication's original contribution. The resulting paper-to-framework analytical record provided the basis for the descriptive theme frequencies, relationships, and qualifying evidence reported in the synthesis and for the subsequent higher-order integration.

4. Synthesis

4.1 Synthesis Process and Framework Development

Building on the validated analytical dataset produced during literature analysis, synthesis focused on identifying and integrating recurring patterns across the 51 paper-level analytical records. Related concepts were organized into conceptual clusters and progressively refined into candidate themes describing common representational processes across the literature.

During refinement, one candidate theme differed from the others because its evidence described conditions that qualified, enabled, or constrained multiple representational processes rather than a distinct process itself. It was therefore reclassified into four cross-cutting principles positioned outside the thematic hierarchy. The resulting framework consisted of seven finalized themes and four cross-cutting principles.

The finalized framework was then systematically applied to all 51 publications, establishing a validated paper-to-framework analytical record. Following framework application, each publication was summarized according to its principal contribution to the thematic framework. These standardized contribution summaries were derived from the validated analytical records and preserved a traceable link between individual-paper findings and the higher-level synthesis. Together, the framework application and contribution summaries provided the evidentiary foundation for synthesis within themes, integration across themes and cross-cutting principles, assessment of the overall state of knowledge, and the integrated knowledge synthesis.

Throughout these stages, synthesis operated from previously validated analytical outputs rather than from renewed examination of individual publications. This preserved a traceable analytical progression from paper-level evidence through framework development and application to increasingly integrated interpretation.

4.2 Theme Synthesis

The validated thematic framework synthesized the literature into seven interrelated themes that collectively describe how external representations support knowledge activity across cognitive, collaborative, material, organizational, and technological contexts. Rather than functioning as independent categories, the themes represent complementary dimensions of a broader representational system. Together, they describe how knowledge is externalized into organized forms, used to support reasoning and sensemaking, coordinated across people and technologies, preserved over time, and

engaged through embodied interaction. The synthesis therefore moved beyond individual studies to identify recurring representational processes supported across the validated corpus.

Two themes formed the strongest conceptual foundation of the synthesis. Structured Externalization of Knowledge established that the transformation of ideas into organized external forms enables relationships among concepts, sequences, dependencies, and categories to become available for inspection and further use. Across diverse representational media—including concept maps, semantic structures, diagrams, knowledge graphs, enterprise models, and physical representations—the literature consistently distinguished meaningful organization from simple external storage or display. The collective evidence showed that organized external representations support articulation, communication, learning, reasoning, decision support, and computational processing by making relational structure accessible for subsequent activity. [1,2,7]

Building on this foundation, Representations as Reasoning Environments demonstrated that external representations function not only as repositories of information but also as active environments in which reasoning occurs. The evidence consistently showed that representational structure redistributes cognitive work by making relevant relationships perceptually available, reducing memory demands, supporting comparison and inference, and enabling users to manipulate information through external rather than exclusively internal processes. Across educational, analytical, professional, and computational settings, reasoning emerged through interaction with organized representations rather than through mental processes alone. [3,4,8]

Two additional themes described how knowledge develops through interaction with external representations. Embodied and Material Engagement with Representations established that bodily action and material interaction can become integral components of representational activity when physical engagement meaningfully alters how represented relationships are explored, interpreted, or expressed. Iterative Sensemaking and Knowledge Construction showed that understanding develops through successive cycles of externalization, inspection, revision, and refinement, allowing incomplete knowledge to remain available for continued development rather than requiring fully formed ideas before expression. Together, these themes characterize representation as an active and evolving process in which understanding emerges through engagement with organized external structures rather than through isolated internal cognition. [1,3,4,9–11]

The remaining themes described how representational activity extends beyond the individual mind across people, time, and technology. Shared Representations and Distributed Knowledge Work demonstrated that organized external representations support coordination across individuals and organizations by providing common reference structures through which participants compare perspectives, negotiate meaning, and integrate complementary contributions. Persistent, Traceable, and Reusable Knowledge established that external representations support continued knowledge use when they preserve the relationships, provenance, and developmental pathways through which understanding was constructed, allowing knowledge to be revisited, validated, communicated, and potentially reused beyond the original activity. Human–Technology Complementarity in Knowledge Systems demonstrated that technologies contribute computational, organizational, representational, and preservational capabilities while humans provide contextual interpretation, domain knowledge, goals, and judgment. Across the validated corpus,

the literature consistently favored complementary interaction between human and technological capabilities rather than technological substitution for human cognition. [1,2,4,34–38]

Across all seven themes, the synthesis identified a common pattern. External representations become consequential not because they exist outside the individual, but because they organize knowledge into structures that can participate in reasoning, support progressive refinement, coordinate distributed activity, preserve developmental context, and enable complementary interaction between humans and technologies. The effects observed throughout the corpus varied according to representational organization, the nature of the interaction, the task, the user, and the context. These recurring patterns provided the conceptual foundation for examining how the finalized themes relate to one another as components of an integrated representational framework.

4.3 Theme Integration

Building on the individual theme synthesis, the seven themes collectively describe an integrated representational system rather than independent processes. Structured Externalization of Knowledge provides the organized external structures through which Representations as Reasoning Environments and Iterative Sensemaking and Knowledge Construction operate. Embodied and Material Engagement with Representations identifies how bodily and material interaction can participate in these processes. Shared Representations and Distributed Knowledge Work extends representational activity across participants. Persistent, Traceable, and Reusable Knowledge extends it across time, and Human–Technology Complementarity in Knowledge Systems extends it through interaction between human and technological capabilities.

These relationships are complementary rather than interchangeable. External organization is distinct from reasoning through organized structures; iterative development differs from long-term preservation; distributed coordination is not synonymous with technological augmentation; and embodied engagement introduces forms of interaction not captured by externalization alone. The literature also identifies tensions within these relationships, including reduced cognitive demands accompanied by increased interpretive complexity, improved coordination alongside possible loss of individual contribution, preservation alongside retention of obsolete information, and computational augmentation that remains dependent upon human interpretation and judgment.

Taken together, the themes explain how organized external representations can support interconnected cognitive, collaborative, embodied, persistent, and technological forms of knowledge activity. This integrated framework provides the basis for examining the conditions under which these processes operate effectively.

4.4 Cross-Cutting Principle Integration

The four cross-cutting principles qualify the operation of the thematic framework rather than describing additional representational processes. Representational Fit and Alignment establishes that effectiveness depends upon alignment among representational form, task, cognitive activity, user, and context.

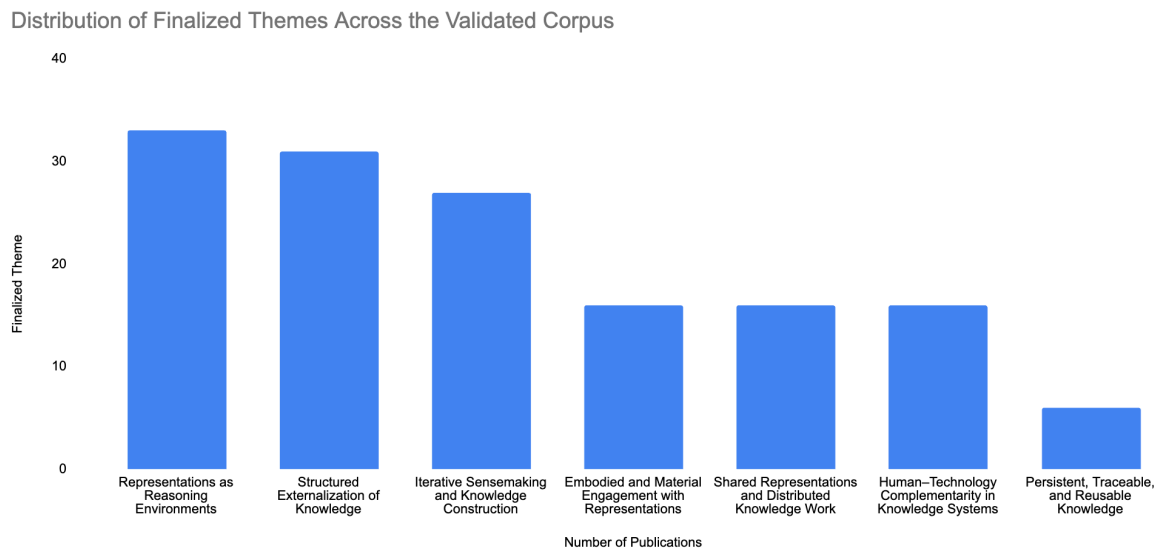
Scaffolding, Facilitation, and Representational Competence identifies the instructional, technical, social, and design support and competence often required for productive engagement. Domain and Contextual Knowledge establishes that interpretation depends upon the knowledge and experience users bring to representations. Representational Integration and Coherence establishes that multiple representations derive value from meaningful relationships among views, modalities, artifacts, and representational states.

Together, these principles demonstrate that the benefits associated with external representation are conditional rather than automatic. The themes describe recurring representational processes, whereas the cross-cutting principles specify conditions that enable, constrain, or qualify their operation. This distinction provides the basis for assessing what the validated literature establishes with greater or lesser confidence.

4.5 Descriptive Characteristics of the Synthesized Evidence

Theme prevalence varied across the seven finalized themes, with individual publications permitted to support more than one theme (Figure 3).

Figure 3. Distribution of Finalized Themes Across the Validated Corpus



Across the 51 publications, 145 validated theme assignments were recorded. *Representations as Reasoning Environments* was the most frequently assigned theme, followed by *Structured Externalization of Knowledge* and *Iterative Sensemaking and Knowledge Construction*. *Persistent, Traceable, and Reusable Knowledge* was the least frequently represented. Overall, thematic evidence was concentrated most strongly in reasoning, structured externalization, and iterative sensemaking, while the remaining themes occurred less frequently.

Because theme assignments were not mutually exclusive, these frequencies indicate the prevalence of each theme across the corpus rather than separate groups of publications. Theme co-occurrence is examined in the following subsection.

4.6 Theme Relationships

Theme co-occurrence was examined across the 21 possible pairwise relationships among the seven finalized themes (Table 2).

Table 2 Pairwise Co-occurrence Frequencies Among Finalized Themes

Theme	Structured Externalization	Reasoning Environments	Embodied / Material	Iterative Sensemaking	Shared / Distributed	Persistent / Traceable	Human–Technology
Structured Externalization		16	6	16	13	4	10
Reasoning Environments			9	17	5	3	10
Embodied / Material				9	2	0	2
Iterative Sensemaking					8	4	8
Shared / Distributed						3	5
Persistent / Traceable							4
Human–Technology							

Theme relationships were unevenly distributed across the corpus. The strongest co-occurrence was between *Representations as Reasoning Environments* and *Iterative Sensemaking and Knowledge Construction* (17 publications), followed closely by the relationships linking *Structured Externalization of Knowledge* with each of those themes (16 publications each). *Structured Externalization of Knowledge* also showed notable overlap with *Shared Representations and Distributed Knowledge Work* (13) and *Human–Technology Complementarity in Knowledge Systems* (10).

In contrast, several relationships involving *Embodied and Material Engagement with Representations* occurred infrequently. *Persistent, Traceable, and Reusable Knowledge* also showed relatively limited overlap with most themes and did not co-occur with *Embodied and Material Engagement with Representations* in any publication. These frequencies describe observed co-occurrence within the validated corpus and provide descriptive evidence for the integrated assessment that follows.

4.7 Qualifying Evidence

Qualifying evidence was examined through the distribution of the four cross-cutting principles across themes (Table 3).

Table 3. Distribution of Cross-Cutting Principles Across Finalized Themes

Cross-Cutting Principle	Structured Externalization of Knowledge	Representations as Reasoning Environments	Embodied and Material Engagement with Representations	Iterative Sensemaking and Knowledge Construction	Shared Representations and Distributed Knowledge Work	Persistent, Traceable, and Reusable Knowledge	Human–Technology Complementarity in Knowledge Systems
Representational Fit and Alignment	15	23	13	18	6	2	11
Scaffolding, Facilitation, and Representational Competence	10	16	10	12	5	0	4
Domain and Contextual Knowledge	20	17	6	15	9	6	14
Representational Integration and Coherence	18	18	7	18	14	6	12

The four cross-cutting principles occurred across multiple themes, but their distributions differed. *Domain and Contextual Knowledge* was represented across all seven themes, as was *Representational Integration and Coherence*. *Representational Fit and Alignment* was most frequently associated with *Representations as Reasoning Environments*, while *Scaffolding, Facilitation, and Representational Competence* was less broadly represented, with no occurrence recorded within *Persistent, Traceable, and Reusable Knowledge*. Overall, the distribution shows that the principles crossed thematic boundaries rather than corresponding to individual themes.

Boundary conditions were recorded for all 51 publications. The analysis identified 38 distinct boundary-condition statements, 32 of which occurred in only one publication. The most frequently recurring statement appeared in eight publications (15.7%) and specified that interpretation depends on relevant domain or contextual knowledge together with coherent integration among representations, views, or system components. A second statement, occurring in three publications (5.9%), specified that application depends on alignment among representational form, task, user, and context together with coherent integration among representations. Four additional exact statements occurred twice each.

Minority or contradictory evidence was likewise assessed for all 51 publications. In 24 records (47.1%), no distinct minority or contradictory finding was recorded. Across the full set of records, 28 distinct entries were identified, 27 of which occurred in only one publication. Where such evidence was present, it was therefore predominantly paper-specific rather than recurrent across the corpus.

4.8 State of Knowledge

The validated corpus supports a coherent but unevenly developed body of knowledge concerning external representation. Across disciplines and representational forms, the literature consistently supports structured externalization, external representations as reasoning environments, iterative knowledge construction, shared representational work, embodied engagement, persistence, and complementary human–technology interaction. Together, these findings indicate that external representation is not a single technique or representational format, but a broader class of knowledge activity operating across multiple contexts.

The evidence is strongest for structured externalization, reasoning support, and iterative sensemaking, which were broadly represented across the corpus and supported across varied contexts. Other areas—including embodied engagement, distributed knowledge work, persistence and reuse, and some forms of human–technology complementarity—were supported by smaller or more specialized bodies of evidence. The resulting knowledge base is therefore substantial enough to support an integrated conceptual account, but not sufficiently uniform to treat all components as equally established.

Across the corpus, representational effectiveness was consistently qualified by context and conditions. The literature emphasized the importance of representational fit, integration and coherence, domain and contextual knowledge, and appropriate scaffolding or representational competence. These recurring qualifications indicate that the field has developed substantial knowledge about both the capabilities and conditions of external representation, while leaving important questions about their interactions, boundaries, and generalizability unresolved.

Accordingly, the current state of knowledge is best characterized as conceptually convergent but empirically heterogeneous: multiple literatures support a common account of external representations as structured environments for knowledge activity, while differences in disciplinary traditions, methods, representational forms, and evidentiary depth limit stronger claims about the generalizability of particular mechanisms or effects.

4.9 Integrated Knowledge Synthesis

Taken together, the validated literature supports an integrated account of external representation as a form of knowledge activity in which information is organized into structures that can be inspected, manipulated, shared, revised, preserved, and used across people and technologies. External representations therefore function not simply as outputs of thought, but as environments through which knowledge activity can occur.

Across the synthesis, these functions are interdependent. Structured externalization makes relationships available for reasoning; reasoning through those structures supports iterative sensemaking and knowledge construction; shared representations extend this activity across individuals and groups; persistence allows

knowledge and its developmental context to remain available over time; embodied interaction can incorporate physical action into representational work; and technologies can extend the organization, manipulation, and preservation of represented knowledge.

These capabilities, however, are conditional rather than inherent to external representation itself. Their effectiveness depends on alignment between representational form and purpose, coherence among representational elements, relevant domain and contextual knowledge, and sufficient scaffolding or representational competence. The synthesis therefore indicates that the consequences of external representation arise from the interaction among representational structure, representational activity, context, and the capabilities of the people and technologies involved.

This integrated account provides the principal synthesis of the review: external representations can function as structured components of knowledge activity through which cognition, interaction, material engagement, collaboration, persistence, and technological capability become coordinated. The literature supports this broader phenomenon across diverse domains and representational forms while also establishing important conditions and limits on how it operates.

5. Discussion

5.1 Interpretation of Major Findings

The synthesis indicates that structured external representations are best understood not simply as containers for information, but as active components of knowledge activity. Across the literature, external representations organize information and relationships into forms that can be inspected, manipulated, revised, shared, preserved, and computationally processed. This organization makes represented relationships available for further action, allowing representations to participate in reasoning and knowledge construction rather than merely recording their outcomes.^{1,4,7}

A central finding is that these functions form an interconnected representational system. Structured externalization makes relationships available for inspection and provides environments in which users can compare, infer, decompose, test, and formulate solutions. Understanding can develop through iterative cycles of inspection, reorganization, and revision, while shared and persistent representations extend knowledge activity across participants and time. Technological systems further contribute computational capabilities alongside human interpretation and judgment. External representations therefore function both as media for cognitive activity and as infrastructure for broader knowledge systems.

These effects do not arise from externalization alone. The literature distinguishes structured externalization from simply recording, displaying, or storing information: represented elements must be organized in ways that expose meaningful categories, relationships, sequences, dependencies, or constraints. Representational properties can redistribute aspects of memory, attention, comparison, inference, and action between the user and the external environment, changing what must be internally maintained, what can be directly perceived, and what operations become available.^{3,4,8}

The findings also show that external representations are not inherently beneficial. Their effectiveness depends on the relationship between the representation and the activity in which it is used. Representational form must fit the task, intended cognitive operation, user, and context; users may require appropriate scaffolding or representational competence; interpretation depends on relevant domain and contextual knowledge; and multiple representations must be integrated coherently. The evidence therefore supports a more precise conclusion: particular representational structures can support particular knowledge processes when the conditions necessary for their effective use are present.

Taken together, the literature identifies organized external structure as an infrastructure through which knowledge can be developed and extended across people, technologies, contexts, and time. External representations can make relationships available for reasoning, maintain incomplete knowledge for continued development, coordinate distributed contributions, and preserve knowledge beyond the immediate activity. These capabilities depend on how representations are structured, interpreted, integrated, and used.

The substantial attrition during cross-domain characterization also identifies a pattern warranting further investigation. Across the three discovery domains, only 41.3% of papers that had demonstrated original domain-specific relevance also satisfied the complementary cross-domain criterion. The pattern was directionally asymmetric: Visual domain and physical/tangible domain origin papers showed similar rates of complementary organizational/verbal domain relevance, whereas organizational/verbal domain origin papers were less likely to demonstrate the complementary visual or physical/tangible criterion. This raises the possibility that relationships across representational forms may be less common, or structured differently, than relevance within individual representational forms. The review was not designed to determine why this pattern occurred, and it may reflect relationships among representational forms, the study's operationalization and search structure, characteristics of the identified literature, or other factors. Future research designed specifically to examine cross-domain relationships could test the prevalence, direction, and meaning of this pattern.

5.2 Implications for the Field

The findings support studying external representations not primarily as discrete tools or formats, but as components of integrated knowledge systems. Convergence around structured externalization, representational reasoning, and iterative knowledge construction, together with collaborative, embodied, persistent, and technological perspectives, provides a basis for studying representations in terms of the knowledge processes they support rather than treating visual, physical, verbal, or computational forms as inherently separate phenomena.

One important implication is that representational research can be framed more precisely around mechanisms and conditions rather than broad representational categories. External representations become consequential through identifiable functions: organizing relationships, making those relationships available for reasoning, supporting revision, coordinating distributed activity, preserving knowledge pathways, and enabling complementary contributions from humans and technologies. These functions are in turn qualified by representational fit, user competence and facilitation, domain and contextual knowledge, and integration among representations. The relevant question is therefore not simply whether

one representational format is more effective than another, but which representational properties support particular knowledge activities, for particular users, under particular conditions.

This perspective also has implications for human–technology systems. The synthesized literature positions technology as a complement to, rather than a replacement for, human knowledge and judgment. Technologies contribute capabilities for computation, organization, visualization, transformation, retrieval, preservation, and formal inference, while people contribute goals, contextual and domain knowledge, interpretation, evaluation, and judgment. Productive knowledge systems therefore depend on representational structures and workflows through which these differentiated capabilities can interact, inform one another, and permit correction and evaluation.^{1,4,12,13}

The findings also indicate uneven development within the evidence base. Support is strongest for externalization, reasoning, and iterative knowledge construction and less developed for persistence and long-term reuse and for several embodied, collaborative, and human–technology mechanisms. The corpus is also concentrated in visual representations and educational and computational settings. The comparatively limited verbal-semantic representation warrants particular caution because differential literature accessibility substantially contributed to this imbalance. It should therefore not be interpreted as evidence that verbal-semantic representation is intrinsically less important and may underestimate its actual presence in the broader literature because relevant publications identified during the review could not all be incorporated when full text was unavailable.

These patterns support deeper empirical refinement of the integrated account established by the literature. Comparative, longitudinal, multimethod, and mechanism-focused research can examine how the identified processes operate across users, contexts, modalities, technologies, and temporal scales. Greater conceptual precision can likewise come from distinguishing the mechanisms through which representations contribute to knowledge activity from the particular media in which those mechanisms occur. The field is therefore positioned to move from establishing that structured external representations matter toward determining more precisely how, when, and under what conditions their particular properties contribute to knowledge activity.

5.3 Strengths of the Review

Several features of the review strengthen confidence in its synthesis. Most importantly, it developed an integrated account from a heterogeneous literature spanning disciplines, methodologies, representational modalities, and empirical traditions. Rather than requiring a common representational format or research design, the analysis identified recurring processes across visual, diagrammatic, semantic, material, organizational, and computational forms. This breadth allowed common patterns to become visible across otherwise distinct areas of research while preserving contextual differences.

A second strength is the preservation of qualifying and contradictory evidence. The analysis did not treat thematic prevalence as evidence of theoretical importance or empirical quality, nor recurring findings as automatically generalizable across contexts. Boundary conditions were retained at the paper level and incorporated into the synthesis, allowing the final account to distinguish what representations can support from the conditions under which those effects occur. This was particularly important because

representational effectiveness repeatedly depended on fit among representation, task, user, and context, as well as representational competence, domain knowledge, and coherent integration.

The review also maintained distinctions among related representational processes rather than collapsing them into a generalized effect of externalization. Structured externalization was distinguished from reasoning with external structures; reasoning from iterative development; collaborative coordination from shared understanding; persistence from mere storage; and technological complementarity from automation or replacement of human judgment. These distinctions allowed relationships among processes to be integrated without erasing their conceptual differences.

Another strength is the analytical restraint applied to the evidence. The corpus combined empirical and nonempirical studies using substantially different methodological designs. Rather than treating this heterogeneous evidence as a basis for estimating effect sizes or making causal or statistically generalized claims, the analysis remained descriptive and interpretive where stronger inference was not supported. This preserves the distinction between convergence in conceptual findings and uniform empirical confirmation.

Together, these features allowed the review to integrate recurring processes across representational forms and research contexts while retaining boundary conditions, minority evidence, methodological differences, and distinctions among representational processes. The resulting synthesis combines breadth with analytical differentiation while keeping the strength of its claims proportional to the evidence from which they were derived.

5.4 Limitations

The findings should be interpreted in light of several limitations arising from the composition of the synthesized corpus and the structure of the available evidence. The evidence base was uneven across disciplines and representational forms. Computer Science and Education accounted for a substantial majority of the final corpus, while visual-origin studies were considerably more prevalent than material-origin and verbal-semantic studies. The synthesis is therefore more strongly shaped by visual, computational, and educational research than by other disciplinary and representational traditions.

The imbalance in verbal-semantic evidence requires additional qualification because it resulted from more than accessibility alone. Cross-domain characterization reduced the originally relevant literature across all three discovery domains, with the greatest reduction among organizational/verbal domain origin papers. Accessibility then produced a separate and disproportionate loss of organizational/verbal domain origin papers that had satisfied the cross-domain criterion. Consequently, the small verbal-semantic component of the final corpus reflects both the study's cross-domain inclusion structure and differential literature access. Its limited representation cannot be assumed to indicate corresponding scarcity or lesser importance in the broader literature and limits our ability to determine how strongly the integrated findings extend to verbally organized representations.

The observed cross-domain scarcity and directional asymmetry also require cautious interpretation. Although these patterns preceded accessibility filtering, the review was not designed to determine

whether they reflect underlying relationships among representational forms, the study's operationalization and search structure, disciplinary differences in the identified literature, or other factors.

Evidence was also uneven across the thematic framework. Structured externalization, representational reasoning, and iterative sensemaking had comparatively broad support, whereas persistence, traceability, and reuse were represented by a smaller and more specialized evidence base. Evidence concerning embodied engagement, collaborative outcomes, and particular forms of human–technology complementarity identified recurring processes but remained more conditional with respect to specific outcomes and configurations. Evidentiary confidence should therefore not be assumed to be equivalent across all components of the framework.

Methodological heterogeneity presents a related limitation. The corpus included empirical and nonempirical publications spanning theoretical analyses, qualitative and mixed-method studies, controlled experiments, quantitative studies, reviews, cases, field studies, and computational work. This diversity supported cross-contextual conceptual synthesis but did not provide a uniform basis for estimating effect sizes, comparing intervention efficacy, or making generalized causal claims. The review therefore establishes convergence in representational processes and qualifying conditions more strongly than the magnitude or comparative effectiveness of particular approaches.

Finally, structured external representation involves trade-offs as well as benefits. Formalized representations can make relationships more explicit, traceable, communicable, and computationally processable, but may also increase demands for navigation, interpretation, and interaction. Accumulated representational states can produce clutter or fragmented histories, while formal structures may incompletely represent tacit, experiential, contextual, affective, aesthetic, or identity-related dimensions of knowledge. Persistent representations can preserve obsolete interpretations, collaborative structures can obscure individual contributions, and increased integration can reduce meaningful differences. External representation can therefore redistribute and reorganize the demands of knowledge activity rather than simply reducing them, and no representational structure should be treated as a complete or inherently simplifying representation of the knowledge, experience, or context from which it was produced.

5.5 Future Directions

The findings point toward a next stage of research focused less on demonstrating that external representations can support knowledge activity and more on determining how particular representational mechanisms operate under different conditions. Because effectiveness depends on relationships among representational properties, tasks, users, and intended cognitive operations, future studies should directly compare specific representational features rather than relying primarily on broad format categories. Comparisons among alternative ways of displaying relationships, integrating representations, embodying information, or enabling interaction could clarify which mechanisms support particular reasoning and knowledge-construction processes and under what conditions.

A particularly direct next step would be a corpus-level secondary analysis that shifts the unit of analysis from the publications themselves to the external representations described within them. Such a study

could mine the validated papers to identify, in the aggregate, what kinds of representational *objects* are actually being created, what makes those objects "explicit instantiations of thought," how their internal organization is structured, and what purposes authors claim or demonstrate for externalizing them. This would allow two related questions to be examined systematically: *What is the structure of these externalized objects?* and *What is the value or purpose of making that structure explicit?* Rather than asking only which themes a paper supports, the analysis could identify what the described representations are made of, how their components are organized, what users are expected to do with them, and what cognitive, collaborative, organizational, or technological consequences are associated with doing so. Such an object-level analysis would provide a more direct bridge between the present paper-level synthesis and further theoretical development concerning the structure and purpose of externalized thought.

Longitudinal research is particularly needed to strengthen understanding of persistence, traceability, and reuse. Existing evidence indicates that preserving provenance, relationships, sequence, and developmental context can allow knowledge to be revisited and evaluated, but provides less evidence about whether these structures remain useful over extended periods. Future studies should examine whether persistent representations remain interpretable, navigable, accurate, and contextually meaningful as users, purposes, organizations, and conditions change. This would help distinguish preservation of a representational record from preservation of a genuinely reusable knowledge pathway.

The uneven representation of modalities also warrants further investigation. Additional research on verbal-semantic, formal semantic, and machine-readable representations could test how broadly the mechanisms identified here extend beyond the predominantly visual evidence base. Such work should examine how relationships are externalized in these forms, how people inspect and intervene in them, and how human-readable and machine-readable structures interact within larger knowledge systems. Given the accessibility constraints affecting the verbal-semantic literature, this is particularly important for determining whether the observed evidence distribution reflects differences among modalities or limitations of the corpus available for synthesis.

Further research is also needed on the conditions that enable effective representational use. The synthesis repeatedly identifies representational competence, scaffolding, facilitation, and domain knowledge as important conditions. Future studies could examine how these requirements vary with expertise, developmental level, task complexity, and representational form, including when support should be introduced, adapted, or withdrawn. Distinguishing immediate performance gains from longer-term development of representational competence could clarify whether a representation merely assists task completion or contributes to a durable capacity to reason with external structures.

Human–technology complementarity presents another area for empirical development. Future research should test complementary arrangements when information is incomplete, models are uncertain, automated outputs are difficult to interpret, or users must identify errors and redirect systems. Evaluation should extend beyond task performance to interpretability, error detection, reciprocal adaptation, and the extent to which representational workflows preserve meaningful opportunities for human judgment.

Finally, research should broaden both the contexts in which representational mechanisms are studied and the outcomes used to evaluate them. Greater disciplinary and methodological diversity could test the

conditional propositions identified here in organizational, professional, community, and other settings less prominent in the current corpus. Multimethod research combining controlled comparisons with situated, longitudinal, and system-level investigation could also examine affective, expressive, material, and social outcomes alongside conventional cognitive or task-performance measures. Such work would deepen the evidentiary foundation of the integrated account while retaining its central insight: the consequences of external representation arise from interactions among representational structure, knowledge activity, users, technologies, and context.

6. Conclusion

6.1 Overall Answer to the Review Question

For this review, the externally instantiated domain relevant to Object-Oriented Thinking (OOT) was operationalized as verbal, visual, and tangible representations that make mental models, information, and organization explicit. This operationalization deliberately bounded the review to observable external representations; it should not be interpreted as making externalization a definitional requirement of OOT. This provided a means of investigating the phenomena encompassed by the emerging concept without deferring to a more confined base of OOT specific literature .

The review asked: **What is the current state of knowledge regarding Object-Oriented Thinking (OOT), operationalized in this study as verbal, visual, and tangible forms of external representation that make mental models, information, and organization explicit?**

The synthesized literature indicates that the phenomena encompassed by this operational definition constitute a coherent and interconnected body of knowledge concerning how structured external representations support knowledge activity. External representations function not merely as containers of information but as organized structures through which knowledge can be externalized, inspected, reasoned with, revised, coordinated, and preserved. They support reasoning and problem solving, iterative knowledge construction, distributed knowledge activity, preservation across time, and complementary interaction between human judgment and computational capabilities.

Taken together, the findings support an integrated understanding of structured external representation in which cognitive, collaborative, persistent, embodied, and technological processes operate in relation to one another. These capabilities are conditional rather than automatic, shaped by representational fit, user competence and facilitation, domain and contextual knowledge, and coherent integration among representations. Although the review did not seek to establish OOT as a validated theoretical construct, it identified substantial existing knowledge concerning the phenomena captured by its operational definition. The resulting synthesis provides an integrated account of how making mental models, information, and organization explicit through external representation can support knowledge activity and the conditions under which that support occurs.

6.2 Principal Contributions

The principal contribution of this review is the integration of a dispersed body of literature into a coherent account of structured external representation across representational forms and disciplinary contexts. The synthesis shows that the phenomena operationalized as OOT are connected not simply by their use of external representations, but by recurring processes through which knowledge is organized into inspectable forms, used for reasoning, progressively developed through iteration, coordinated across people and technologies, and preserved across time. The review thus brings cognitive, collaborative, persistent, embodied, and technological dimensions of representation into a common explanatory account.

A second contribution is the identification of conditions that qualify these processes. The literature does not support a general proposition that externalization is inherently beneficial. Rather, representational effectiveness is shaped by alignment with purpose and context, user competence and facilitation, relevant domain and contextual knowledge, and coherent integration among representations. This conditional account shifts attention from whether external representations support knowledge activity to how and under what conditions they do so effectively.

Together, these contributions provide an evidence-based foundation for understanding the representational phenomena encompassed by OOT from the broader literature base. The review therefore provides both an integrated account of the existing knowledge base and a basis for further theoretical refinement and empirical investigation of the emerging concept.

6.3 Implications and Future Work

The findings provide an evidence base for the continued development of Object-Oriented Thinking while also defining important limits on that development. The review indicates that future development should preserve the distinction between the evidence-supported representational processes identified in the synthesis and theoretical claims that extend beyond the current corpus.

A particularly direct next step is to move from the present paper-level synthesis to an object-level analysis of the representations described within the validated corpus. Such work could examine what the literature treats as the externalized objects of thought, how those objects are structured, what purposes they serve, and what value is associated with making that organization explicit. This would provide a more precise empirical and conceptual basis for determining what, exactly, is being externalized and why.

The research priorities identified in the Discussion provide additional pathways for strengthening this evidence base through further empirical and theoretical investigation. Collectively, these directions can clarify the mechanisms, boundary conditions, representational forms, and contexts through which external representations support knowledge activity. Such work would allow future formulations of OOT to develop in closer correspondence with accumulated evidence while remaining open to revision as the underlying knowledge base expands.

6.4 Closing Statement

This review began with an emerging concept and a deliberately provisional operational definition. We examined the existing literature concerning one observable manifestation of this broader phenomenon: verbal, visual, and tangible external representations through which the organization of mental models and information is made explicit. The resulting synthesis demonstrates that these phenomena are supported by a substantial and conceptually coherent body of knowledge concerning the role of structured external representation in knowledge activity.

Across this literature, external representations emerge as more than artifacts produced by thought. They form part of the processes through which knowledge is organized, examined, developed, shared, preserved, and extended through interaction with other people and technologies. At the same time, their effectiveness depends upon the purposes they serve, the people and contexts in which they are used, and the ways in which different representations are integrated.

The significance of OOT therefore lies not in treating the concept as established by this review, but in the opportunity it provides for bringing these related representational phenomena into a common focus for continued investigation. The evidence synthesized here provides a foundation from which OOT can be more precisely defined, theoretically developed, and empirically tested. In doing so, future research can move from a provisional organizing concept toward a clearer understanding of what is made explicit through structured external representation, how that structure is organized, and what value arises from making it available for individual and collective knowledge activity.

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Appendix and Supplementary Materials

Supplementary Analytical Materials

The first four supplementary tables provide the principal analytical record underlying the synthesis. **S1 – Analysis Paper-Level Records** presents the individual-paper analytical record for each publication in the validated corpus, including what each paper did and what it reported. **S2 – Phase 3 Paper Application** presents the paper-level application of the finalized analytical framework. **S3 – Phase 3 Evidence Matrix** provides the paper-to-theme evidence matrix summarizing thematic support across the corpus. **S4 – Paper Contribution Summaries** presents the standardized contribution summaries used to support the integrated synthesis.

Together, these materials preserve the analytical progression from individual-paper findings through framework application and corpus-wide thematic mapping to the contribution summaries supporting the integrated synthesis. They provide a transparent audit trail from the source literature to the synthesized findings reported in the manuscript.

1. Analysis Paper-Level Records

S1 – Analysis Paper-Level Records presents the individual-paper analytical record for each of the 51 publications in the validated corpus. For each publication, the worksheet records the paper ID, title, authors, what the study did, what it reported, discipline, primary methodology, methodological subtype, empirical status, and a standardized analytical narrative.

The table provides the principal supporting record for the paper-level findings reported in Section 3.3. In particular, the *What Did They Do?*, *What Does It Say?*, and narrative fields preserve what was identified from each publication before thematic synthesis. The worksheet therefore allows readers to examine the individual-paper evidence underlying the manuscript's account of what the 51 publications contributed to the review.

2. Paper-Level Framework Application

Building on the individual-paper analytical record, **S2 – Phase 3 Paper Application** presents the application of the finalized analytical framework to each of the 51 publications. For each publication, the table reports the assigned finalized themes, supporting analytical justification, cross-cutting principles, identified boundary conditions, and any minority or contradictory evidence recorded during framework application.

The table preserves the analytical connection between individual publications and the integrated findings reported in the manuscript. Theme and cross-cutting-principle assignments are presented as paper-level analytical results rather than characteristics inferred from bibliographic information alone. Where the

analysis did not identify distinct minority or contradictory evidence, the corresponding record states this explicitly rather than introducing an interpretation beyond the validated analysis.

3. Paper-to-Theme Evidence Matrix

Building on the detailed framework application in **S2 – Phase 3 Paper Application**, **S3 – Phase 3 Evidence Matrix** provides the paper-to-theme evidence matrix for the 51 publications in the validated corpus. The matrix maps each publication to the seven finalized themes and identifies the cross-cutting principles assigned during framework application.

The matrix provides a corpus-level view of how thematic support is distributed across publications. Because themes were not mutually exclusive, it preserves multiple assignments where a publication supports more than one dimension of the finalized framework. In this way, S3 makes visible both the breadth of support for each theme and the overlap among thematic contributions.

Used together, S2 and S3 provide complementary levels of analytical traceability. S2 retains the detailed evidence and justification underlying paper-level framework application, whereas S3 provides a compact representation of those assignments across the full corpus.

4. Paper Contribution Summaries

S4 – Paper Contribution Summaries presents a standardized contribution summary for each of the 51 publications in the validated corpus. These summaries capture how each publication contributed to the review's representational framework and provide a consistent account of its role in the synthesized understanding of external representation.

The contribution summaries provide an intermediate bridge between detailed paper-level analysis and the higher-level synthesis. Whereas S1 preserves what individual publications did and reported, S2 documents the evidence and justification supporting framework assignments, and S3 maps those assignments across the corpus, S4 condenses each publication's contribution into a standardized narrative form.

Together, S1–S4 establish a linked analytical record extending from individual-paper findings through framework application and corpus-wide thematic mapping to concise statements of individual-paper contributions.

5. Descriptive Tables

S5 – 4A.1 Corpus Characteristics, **S6 – 4A.2 Theme Characteristics**, **S7 – 4A.3 Theme Relationships**, and **S8 – 4A.4 Qualifying Evidence** present the validated descriptive outputs generated during analysis.

S5 summarizes the characteristics of the validated corpus. S6 reports the prevalence and distribution of the finalized themes. S7 presents relationships among themes. S8 summarizes the cross-cutting principles and qualifying evidence, including boundary conditions and minority or contradictory evidence identified during the validated analysis.

Together, S5–S8 provide the descriptive analytical foundation underlying sections 5.5 - 5.7 in the Synthesis section and support the interpretations presented in the Synthesis and Discussion. Their inclusion allows readers to examine the distributions, relationships, and qualifying evidence underlying the manuscript narrative without reproducing the complete descriptive record in the main text.

6. Methodological Supporting Documents

Additional supplementary materials preserve methodological records supporting the transparency and reproducibility of the review. **Supplementary Document S9 – Screening Corpus Integrity Audit** documents the audit conducted to verify the completeness and internal consistency of the abstract-screening corpus before subsequent cross-domain analysis. The audit verified the expected screening conversations across all three discovery domains and identified no evidence of missing, duplicated, or truncated screening conversations or other obvious corpus omissions.

Supplementary Document S10 – Cross-Vector (Domain) Characterization Report documents the second-level characterization used to identify complementary representational properties among papers that had already satisfied the inclusion criteria for their original discovery domains. It records the distinction between initial corpus selection and subsequent representational characterization, the four directional cross-domain comparisons, their operational criteria, and the resulting abstract-level characterization of the candidate corpus.

Together, these methodological documents preserve key procedural records underlying corpus construction and characterization without reproducing those details in the main manuscript.

Collectively, **S1–S8 and Supplementary Documents S9–S10** preserve the principal analytical and methodological records supporting the review. They provide traceability from corpus construction and characterization through individual-paper analysis, framework application, thematic integration, and the descriptive findings reported in the manuscript.

Replication files are available from the author upon request.