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REVIEW ARTICLE

The Knowledge Action Ontology: a description of the cognitive actions of engineering design

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ABSTRACT
Design is a cognitively intensive activity requiring designers and engineers to interact with a multitude of knowledge to create solutions for complex problems. This article reviews eight design research journals to understand the cognitive actions that allow knowledge to inform design. The Knowledge Action Ontology (KAO) was derived as a descriptive framework that outlines five cognitive actions – *Recognize*, *Gather*, *Use*, *Evaluate*, and *Integrate* – that enable knowledge to inform design. This research outlines the characteristics of each knowledge action and provides examples and evidence of the nature of the different cognitive actions. The KAO is mapped to the design process to describe the cognition of applying knowledge within design. This ontology introduces common language and informative definitions for design cognition researchers and practitioners alike. The ontology sheds light on the complex cognitive dynamics and behaviours of enacting knowledge within the design process.

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Design cognition; design knowledge; engineering design; cognitive actions; design process

1. Introduction

When considering how practitioners approach design, it is possible to see that conducting design is a very complex process. Research has synthesised a myriad of behaviours to describe the process of conducting design (Ullman 2010), as well as many best practices of doing design within diverse contexts and situations (Yilmaz et al. 2016). Researchers have also investigated the cognition of doing design to describe the ways practitioners leverage their minds when doing design (Hay et al. 2017b). The two key paradigms of design cognition describe design as either search or exploration. In the design as search paradigm, design is seen as a process of transforming knowledge within a problem space to find a solution. In the design as exploration paradigm, design is understood as operating between problem and solution spaces, with the designer's understanding of both spaces being crucial to finding the right solution.

The second paradigm is grounded in Donald Schön's reflective practice (Schön 1983), which describes the process designers undergo when leveraging their minds to interact with the complex situations of design practice. Within his theory of reflection-on-action,

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Schön describes practitioners as interacting with the situations by naming, framing, moving and reflecting on their work. These four activities form the basis of reflective practice, in which practitioners can adapt to the changing landscape and understanding of their problems. Within reflective practice, designers leverage their knowledge (formal and experiential) to perceive [name] and understand their design spaces [frame] to inform their approach solving [move] and verify their solutions [reflect] (Schön 1983). Through this process, the practitioner's knowledge becomes the constraining factor of what can be seen and interacted with in the design space. This knowledge constraint is the impetus of this research.

Since the conception of reflective practice, researchers from many disciplines have been working to understand the intricacies of reflective behaviours. Many studies have found results related to how designers interact with the external aspects of the problem setting and solving processes (Zheng 2015); however, only a handful of studies have focused on the intricate behaviours of a practitioner's internal cognition (Hay et al. 2017a). Many of these studies have been conducted under the concept of design frames, which under some definitions describe the conceptual structure of their design approach (Kelly and Gero 2022). The work in this paper is focused on synthesising the existing findings of literature to describe the internal workings of how practitioners leveraged their knowledge when conducting design.

The goal of this work is to develop a clarified, yet simple, description of how practitioners enact their knowledge in design. We will describe the cognitive actions that enable knowledge to support and constrain a designer's process. The work will pull on diverse fields to ground the findings in cognitive science, psychology, learning science, as well as design cognition. The results of this paper will inform design researchers and practitioners alike about the complex, nuanced, and potentially limited ways designers' knowledge enables and supports successful design projects.

2. Background

2.1. Definition of knowledge

As described above, knowledge in this research is situated as the constraining factor in how a designer perceives and conceptualises design spaces. The task of defining the concept of knowledge and knowing has been the subject of deep and varied philosophical discussion for centuries (Bolisani and Bratianu 2018; Neta and Pritchard 2009). There have been two main perspectives on knowledge, rationalism and empiricism. Rationalism is grounded in Plato and built upon by Descartes, stating that knowledge comes from reasoning processes that are not impacted by sensory experiences (Descartes 1997). While empiricism, adopted by Aristotle and continued by John Locke, states that knowledge is created through our sensory interface with the real world (Russell 2004). In short, both theories accept a well-known definition that *knowledge is justified true belief*.

Within this definition, three conditions stand out to describe the concept of knowledge: first, being the truth condition, which requires one to know the proposition to be true; second, the belief condition, which demands the person to believe in the truth of the proposition; and finally, the justification condition, which states that the practitioner must have a practical way to justify the truth of the belief (Bolisani and Bratianu 2018; Neta and Pritchard 2009).

Going further in the study of knowledge, knowledge has been described through metaphors, such as knowledge as objects (Andriessen 2006), knowledge as nuggets (Delen and Al-Hawamdeh 2009; Williams and Huang 1997), knowledge as an iceberg (Nonaka 1994), knowledge as a flow (Bolisani and Oltramari 2012), and most recently, knowledge as energy (Bolisani and Bratianu 2018). Within this research, the complexity of the conceptualisation of knowledge and the depth of philosophical interest and debate are important to note and honour. We will be describing knowledge in this research as an object as well as energy that can be stored, applied and moved throughout one's cognition.

Beyond the definition of knowledge, several other concepts are important in describing the unit of knowledge. Specifically, data and information are commonly cited as related concepts. Data is basic, unrefined and unfiltered information. Information is refined data that has evolved to being useful for analysis. Knowledge, within this comparison, resides in the user, where human experience and insight is applied to data and information (Kelley 2002; Liew 2007; Zins 2007). This distinction is important in many contexts; however, we believe it to be arbitrary in the context of this study. The term information will be used relatively interchangeably with the term knowledge due to the cognitive focus of this investigation. Several papers will use the term information, which, when considered through the lens of individual cognition, is relevant to our curiosities regarding knowledge within design.

2.2. Memory

The storage mechanisms of knowledge have also been well studied as memory (Rumelhart and Ortony 2017). The conceptualisation of memory has gone through many iterations to better articulate and model the complex and time-dependent processes of generating and retrieving memories. Several key structures of memory have remained constant through the vast evolutions of the theories. These structures are working memory and long-term memory (Miyake and Shah 1999; Shah and Miyake 1999). The construct of working memory, in psychological theory, is the system or mechanism that maintains task-relevant information during the performance of a cognitive task (Baddeley 2003; Daneman and Carpenter 1980). The construct of long-term memory describes the systems and mechanisms that afford the encoding, maintenance, and retrieval of information over periods of time (Atkinson and Shiffrin 1968). Many models show how working memory and long-term memory build on each other. For example, Norman considers working memory as an activated portion of long-term memory representations (Norman 1968). Other researchers described a long-term working memory model to alleviate the constraints around working memory in unfamiliar tasks, interruptions, and activity completion (Ericsson and Kintsch 1995). These models exemplify the complex and interconnected nature of the various layers of memory.

Within the present research, the constructs of working memory and long-term memory will be combined with concepts of memory storage beyond the conscious applications of knowledge. There is a lot of discourse around the application of the subconscious, intuition, or other non-conscious constructs. Often in psychology, intuition is known as a fast structure, where immediate reactions suggest intuitive insights (Brusovansky, Glickman, and Usher 2018; Kahneman 2011). However, with an expanded curiosity, intuition has been seen cited by many other scholars as existing within other constructs (Dane and Pratt 2007). For example, within philosophy, western philosophers understand intuition to be the most pure and immediate way of knowing, representing inborn or divine knowledge (Osbeck 2001). Or within eastern philosophy, perceptions of intuition grounded in Buddhist views describe intuition as a means of connecting to penetrating knowledge, such as a 'gateway to richer world' (Guenther 1958). Intuition has also been seen to be connected to expertise, in which, as more knowledge and experience is acquired, practitioners are better able to access appropriate and correct intuition for the task at hand (Baylor 2001). Each theory of intuition shows that the mechanisms that maintain and support unconscious knowledge are complex.

Within the research, these memory structures will be described in relation to the dynamics of knowledge in design. To clarify the granularity of the theories being built upon in this research, working memory and long-term memory will be described as separate levels of cognition, in which long-term memory supports the enactment of working memory, and working memory feeds into long-term memory. Similarly, to describe the unconscious memory structures, the term 'subconscious' will be used to describe the mechanisms that leverage intuition and other structures of the unconscious. This subconscious layer of understanding the application of knowledge in design will similarly interact with the constructs of long-term memory, and thus also with working memory in the retrieval, inspiration and maintenance of the knowledge that flows between each layer of knowing and memory.

2.3. *Importance of knowledge in design*

When considering knowledge within design, it is important to understand that doing design is an incredibly cognitive task, in which designers need to understand their problem and develop models to transform the available resources and constraints into a viable solution (Hay et al. 2017b, 2020). This requires a notable number of cognitive faculties to ensure the proper information is applied (Cross 1986). Researchers have investigated the type of knowledge important to designers (Horváth 2022). One researcher derived 24 types of knowledge important to conducting design, as seen in a case study. This knowledge was split into three categories, namely, managerial knowledge, process knowledge, and product knowledge, which indicate the exact categories of knowledge necessary to conduct a design project (Ahmed 2007).

As seen above, knowledge about the process of design is important. Often design is seen as a skill where learning how to design is part of the necessary knowledge of doing design. There are many design theories to describe how to cognitively approach design by applying particular frames to design problems (Rodriguez and Benavides 2021) or how to educate a designer to ensure they are approaching their design problems with incremental knowledge acquisition (Oxman 1999). Within engineering, there are findings that pure methods knowledge is important, as it allows practitioners to frame the knowledge they apply within diverse problems (Stacey et al. 2025).

When working in a specific context, or with particular products, it is necessary to have a working knowledge about the situation at hand. This type of knowledge provides nuance to what information is most applicable to the design (Bertola and Teixeira 2003; Cross

2004). Similarly, different domains require a different understanding of how to approach the details of the problems each discipline faces (Carvalho, Dong, and Maton 2009).

In the categorisation above, managerial knowledge was also found to be important in design; other researchers have detailed this point as well. Namely, researchers have found that planning and interpersonal skills are important while conducting design projects (Zika-Viktorsson and Ritzén 2005). These skills are necessary for ensuring the project stays on track and project details are communicated. It has also been found that several types of general disciplinary knowledge are useful to conducting design. For example, knowledge about psychology (Carbon 2019) or circular economies (Ruiz-Pastor et al. 2022) has been found to be useful to conducting successful design projects, in which solutions are generated in a timely and aligned manner.

Overall, having knowledge about the product, how to approach a design process, and how to manage a design process is necessary to successfully conduct design. However, although this literature highlights the importance of such knowledge, it does not show exactly how a designer applies this knowledge in design.

2.4. Models of design

Beyond the types of knowledge designer's use, it is important to understand the current landscape of models that support designers' cognitive approach design.

One way models have been applied to capture cognition is mental models (Johnson-Laird 1983). These structures are an organisation of knowledge, focused mainly on technical domains, that reflect beliefs about a system, correspond to parameters, and help anticipate behaviour (Gentner and Stevens 1983). Other research has been conducted to investigate mental modelling schemes, in which both an internal and external representation is developed to assist practitioners in solving problems. Internal and external representations are often discussed within the concept of distributed representation, where cognitive tasks are shared between the two. These representations create interaction, with internal representations being mental models of a problem and external representations serving as essential cognitive aids (Zhang 1991). Internal representations can be categorised into four types: propositional, analogical, procedural, and parallel/distributed (Rumelhart and Norman 1983). External representations include physical symbols, objects, or rules embedded in the environment (Zhang 2000). They enhance cognitive abilities by making thoughts shareable, aiding re-representation, and facilitating computation (Kirsh 2009). These mental models and descriptive representations are not themselves cognitive actions; rather, they allow designers to inform their design processes with knowledge. These concepts are pulled upon within the discussion of the findings.

To shift the focus of cognitive models in design, functional models of artifacts are often implemented in order to support cognition. Functional models are constructed to describe the devices, products, objects and process with a particular interest in how each of these entities function and how each of the subcomponents interact and function with regard to each other (Erden et al. 2008). These models describe the action each artifact can take, and they provide tools to help support the cognition of a designer as they explicitly determine the important aspects that enable systems and mechanisms to become dynamic. However, they themselves are not models of cognition.

A similar modelling technique is the Function-Behavior-Structure (FBS) ontology, derived by Gero (Gero 1990). The FBS ontology describes all designed things through a processes-oriented lens to distinguish the stages and iterations undergone when producing an artifact (Gero and Kannengiesser 2014). This ontology describes design as a transformation between different states of Function, Expected Behavior, Structure, Structural Behavior, and Description. Eight distinct steps are defined to iterate through these states within the ontology, which describe the design process, irrespective of discipline (Dorst and Vermaas 2005). This ontology has been widely used to investigate aspects of how designers approach design.

This ontology has gone through various iterations itself; one notable iteration is the derivation of the "situated FBS ontology, which brings into attention that design typically moves between three worlds: the external world, the interpreted world, and the expected world (Gero and Kannengiesser 2004). This addition has continued to describe the nature of design through a functional, behavioural and structural lens. When utilising this ontology, researchers analyse the behaviours of the designers to investigate their design process approach. This lens of analysis has provided significant insight into how designers conduct design; however, it does not properly investigate the cognition of designers as they work on design problems.

There has been a limited number of models to describe designers' cognitive approaches to design. One notable approach was conducted by Suwa et al. in which they derived a scheme to code cognitive actions in protocol analysis data (Suwa, Purcell, and Gero 1998). Within their scheme, four distinct cognitive action categories were defined: physical, perceptual, functional and conceptual. Each of these categories had subcategories and particular actions to define the cognitive behaviours of the designers. Within the study that derived these categories, the team found insights into the importance of sketching as an external memory source, as well as a setting for thoughts to develop. Though this analytical lens provides interesting perspective on how designer cognition can be studied, it does not itself describe the actions that are undergone when designers apply knowledge in design.

These examples of models of design work are informative in various ways; however, they do not describe the internal dynamics of doing design with one's accessible knowledge. The work conducted in the current study seeks to fill that gap by investigating previous research in design knowledge applications to understand what previous researchers have learned thus far. Our focus within this work is on individual cognition. There is a magnitude of work investigating how practitioners are impacted by external technological or social systems (Allison et al. 2022; Cash, Dekoninck, and Ahmed-Kristensen 2017; Dougherty et al. 2026; Khanolkar, Vrolijk, and Olechowski 2023). However, the interest of this work is the pure cognition of an individual practitioner. With this focus, the findings of our research will describe the basic cognitive building blocks of a singular agent. This can then be applied to more complex scenarios to consider the influence of teams, artificial intelligence, or other external support systems with regard to design problem solving. Our analysis seeks to examine individual designers to bridge the gap between knowledge, memory, and design, to gain a better understanding of how knowledge can impact design.

3. Methods

3.1. Data collection

The intention of this literature review was to investigate how designers apply their knowledge. This question was approached through a scoping literature review (Munn et al. 2018). Article collection began with database selection. Due to this research focusing on design cognition, a set of eight journals that focus on design cognition and relevant topics were selected as the search space. The journals are *Journal of Mechanical Design; Design Studies; Artificial Intelligence for Engineering Design, Analysis and Manufacturing; Research in Engineering Design; Journal of Engineering Design; Design Science Journal; Journal of Computing and Information Science in Engineering; International Journal of Design Creativity and Innovation*. These journals were chosen due to their importance to the field and the perceived applicability to the research topic.

Within each journal archive, 16 terms were used to search the title, abstract and keywords. The 16 search terms are as follows: *cognition, cognitive structure, expertise, framing, heuristics, identification of needs, information gathering, information introduction, knowledge, knowledge representation, knowledge structure, knowledge usage, mental models, problem exploration, task analysis, task clarification*. The search terms were selected to express a breadth of topics relating to the study of knowledge within design. They were also selected to describe potential known applications or mechanisms of knowledge within design, i.e. information gathering, identification of needs, task classification.

The literature set was collected between 5th and 12th July 2022. The article identification phase resulted in a total of 2585 unique papers. The first stage of filtering included reading each title and determining its applicability to design cognition. This title filter resulted in 810 papers that appeared to describe how designers interact with their knowledge while doing design. Following the initial title filter, a subsequent abstract filter was conducted in which each abstract was reviewed, the key topic of the paper was extracted, and the pertinence of the article was determined. Articles were included in the review if the abstract suggested the paper provided insight regarding the cognition or cognitive actions in which knowledge was applied by a designer. Papers were excluded if they described physical behaviours, analytical methodologies, or research about the organisation of external knowledge storage systems. The filter was implemented to select papers that described the internal cognitive behaviours, as opposed to external physical behaviours of the designer. The goal of this filter was to exclude papers that described specific techniques, methods, or tactics to approaching design. We sought to capture a broad understanding of all the different ways designers apply their knowledge from a cognitive perspective.

From this abstract filter, a total of 148 papers were included in an in-depth analytical literature review. Each paper was read in detail, analysing the relevant methods, discussions and conclusions, which were extracted and synthesised to derive the results of the paper. Through the analysis, a consistent category of designer support tools was discovered. Papers that fell in this category described external tools, such as methods, models, or systems created to support designer knowledge application in design. There were 53 articles of this type in the in-depth literature review. This current article does not report on those findings, as support tools fall out of scope for defining the knowledge actions of designers. Also, 11 papers were found to describe the importance of knowledge in design,

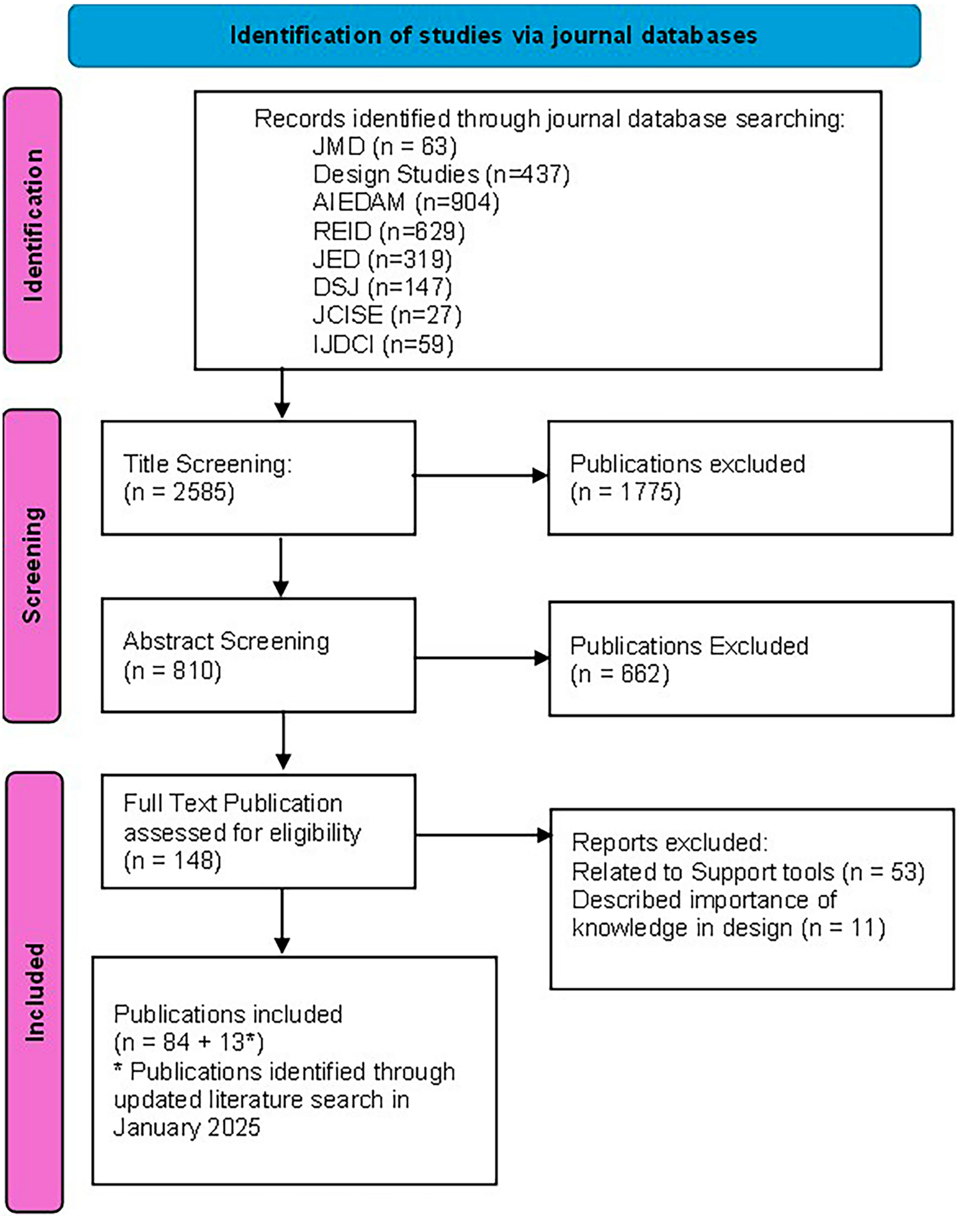

Figure 1. . PRISMA flow diagram for scoping review including searches from journal databases. A total of 2585 papers were initially reviewed, resulting in a final literature set of 97 articles.

which were cited within the introduction and are not included in the final literature set. Thus, from this analysis, a total of 84 articles were found to be relevant to the dynamics of designer knowledge. The following section describes the analysis of the full 148 article set. The full collection and filtering process is shared in a PRISMA diagram in Figure 1.

Following the completion of the analysis, 13 supplemental documents were added to the data set to update the literature set from the original July 2022 collection to January

2026. The files were collected from the same eight journals using the terms 'knowledge' and 'cognition' in a content search. The search results were subjected to a title and abstract filter, leaving the final 13 files. In total, the results of this literature review present findings from 97 articles within eight key design journals. The full breakdown of the collection process can be seen in the PRSIMA diagram in Figure 1.

3.2. Data analysis

The review was primarily conducted by the first author, with major support from the second and fourth authors. The first author conducted the initial article extraction and title and abstract filters. The second author then collaborated in reading, analysing and synthesising the papers to extract key findings. Through this collaboration, weekly meetings with the fourth author supported the team in collaboratively deriving the KAO. The KAO characteristic analysis was conducted mainly by the first author, with continual check-ins with the fourth author. As the process of finalising the structure of the literature review was highly iterative, the research team met constantly to address uncertainties, clarify discrepancies and verify theory. The final stage of this study was a mapping of the KAO onto the design processes. Operationalising the KAO was conducted by the first and third authors and is described in more detail in Section 5.3.

The analysis of the literature set was systematic, yet exploratory in nature. The literature review was intended to give an overview of how knowledge had been investigated within the field of design cognition. The driving question for this research is: **What cognitive actions allow knowledge to inform a practitioner's design process?**

To begin the analysis, papers were sorted thematically several times to assist the researchers in approaching the task of reading, analysing, and determining a structure of synthesis for the literature review. The topics of the literature set were broad, as the search terms would suggest; however, several key concepts arose, as they reflect the ways in which knowledge has been studied within design. These common topics include *knowledge-based system and neural networks, design knowledge in teams, knowledge reuse, design theory, methodology and philosophy, design expertise and framing, cognitive and design processes, and categories of knowledge*, among other topics.

3.3. Deriving the KAO

With these relevant concepts providing an understanding of the content of the literature review, several themes began to inductively arise. As the research team read each paper, the above research question was answered through several reoccurring concepts. Namely, the teams approached the literature with a lens to investigate how designers *recognise*, *gather*, *use* and *integrate* knowledge within their process. As the analysis continued, however, several papers seemed to describe concepts that fell outside of this four-action analytical lens.

This prompted the research team to verify the research lens by comparing against Bloom's Taxonomy of learning styles to notice any overlap, and gaps (Bloom et al. 1956; Krathwohl 2002). Bloom's taxonomy describes six cognitive activities arranged in order of complexity to support and describe educational goals and learning outcomes. Investigating Bloom's taxonomy highlighted a key cognitive of validating, assessing, and justifying

Table 1. Knowledge action ontology (KAO).

Action	Definitions
Recognise	The action of seeing, noticing and perceiving information and its importance, due to the knowledge that is accessible within the practitioner's cognition.
Gather	The action of acquiring information that is not already accessible within the designer's cognition.
Use	The action of applying knowledge to analyse information, make decisions and construct logical arguments in a design space.
Evaluate	The action of verifying and validating knowledge and its applications. The critical reflection on the knowledge, the context, the modelled solutions and/or the complex outcomes.
Integrate	The action of assimilating knowledge into the designer's inherent cognitive processes to develop design judgment, instinct, and intuition.

learning outcomes. This comparison offered the research team guidance to add an additional research lens of how designers *evaluate* their knowledge in design. With this final action added to the list of descriptive activities, the analysis frame was finalised. Definitions of each action were written and acted as a guide to further data analysis (Table 1).

This analysis lens was termed the Knowledge Action Ontology and provides descriptive detail about the dynamic process designers undergo when applying knowledge in design. Using this finalised ontology scheme, the full literature set of 148 articles was reviewed once more to extract the key takeaway as related to the KAO. Again, the results in this paper report on only 84 original papers, as they inspired and provide the core description of the KAO. The 13 additional papers were cataloged into the finalise ontological structure.

3.4. KAO characteristic analysis

Once the KAO was defined, a further detailed analysis of each article was conducted to determine the characteristics of each knowledge action. Each paper was correlated with one knowledge action as a result of the derivation of the ontology. As design is an incredibly complex process, multiple actions were seen to be described within one report. However, for ease of analysis, the articles in this literature review were synthesised to extract the most prominent knowledge action for each paper. This was done through a detailed content analysis of each article to understand the goals, methods and main conclusions of each article. A summary of each article was written to summarise the key findings of the article without consideration of the KAO. The articles were then considered with respect to the KAO to conduct a triangulation of the goals and key findings to understand the core knowledge action being studied within the article. Once the core actions were determined, a summary of the aspects of the articles which connected them to the knowledge action was summarised. This was a highly iterative process in which articles were re-read continuously to ensure contents were properly extracted.

Through this approach, a thematic analysis to inductively determine the characteristics of the knowledge actions were also conducted. The thematic analysis began by reviewing the summaries of the contents and the statement regarding how the article connected to the knowledge action. The articles within one knowledge action were sorted based on the two summaries, and themes began to arise. Similar articles were clustered and statements regarding thematic characteristics were written. Throughout the process of defining

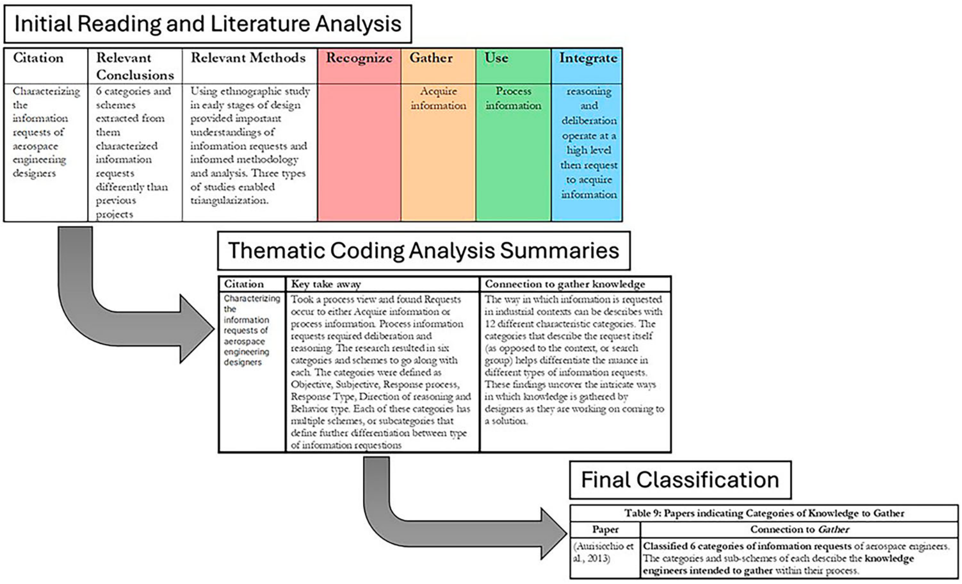

Figure 2. . An illustrative example of the analysis of (Aurisicchio, Bracewell, and Wallace 2013) to represent the synthesis structure of the 84 original papers in the literature review.

themes, articles were audited to verify the contents were properly summarised and synthesised. Several iterations of redefining themes and shifting articles between themes were conducted until themes remained stable with the original 84 articles. Once the thematic structure was saturated, which sometimes left a theme with only two related papers, the summary and connection statement of each article were further simplified into a single descriptive statement, which is reported below. Due to the many iterative steps of content analysis; the research team attentively articulated the contents to ensure data loss was minimised.

To provide an illustrative example, we will use Aurisicchio, Bracewell, and Wallace (2013) to show how papers moved through the analysis process. Figure 2 presents the stages and the extracted information that supported the analysis of the 84 original papers in this literature review. With the first stage of analysis, before the ontology was fully defined, each article was compared to *recognise*, *gather*, *use* and *integrate* knowledge. This article indicated as being related to *gather*, *use,* and *integrate* knowledge based on the paper's stated goal to investigate how aerospace engineers 'acquire information' (*gather*), 'process information' (*use*), and how the engineer's 'reasoning and deliberation operate at a high level and then request to acquire information' (*integrate*).

Once the full ontology was defined with its 5 knowledge actions, all papers were correlated with one action. This paper was determined to be most relevant to the *gather* action based on the relevant conclusions and methods, which suggested the article looked primarily at the requests for information from the engineering designers, a form of acquiring information, thus suggesting its relevance to *gather*.

From this original categorisation, the paper was read in detail to extract key takeaways, and a paragraph describing the connection to the knowledge action was written. This outline informed a comparative thematic analysis. The article was classified through several iterations of themes including: 'Formal information requests', 'What types of information can be gathered', 'more structures/taxonomies of knowledge' and finally 'Categories of Knowledge to Gather'. A final, shortened statement of the article was written to simplify the lengthy summaries from the previous stage. This was the final step of the analysis and is presented in the results section in Table 9.

The additional 13 articles were analysed within the existing thematic structure. The contents of these papers were analysed deductively to determine: first, which knowledge action they related to, and second, which characteristic they best supported. The summaries of each article were extracted to meet the simplified description of the previously synthesised articles.

3.5. Method of operationalizing the KAO

The final stage of this research seeks to uncover how cognitive actions allow knowledge to inform a design process. To investigate this, the derived knowledge actions are related to a design process. Within this final step of the analysis, the knowledge actions will be mapped to a design process.

Many researchers have identified and articulated the stages of the design process (Adams & Atman, 1999; Wynn & Clarkson, 2018; Moore et al. 1995). Each classification of design process emphasises a different aspect of the complex process of design. Moore et al. defined 10 common stages of design through a literature review of engineering textbooks (Moore et al. 1995). This classification was chosen to describe the design process within this study, as this research is working to support further analysis of engineering design cognition. Further, this design process classification has been the grounding of significant engineering design research regarding expertise and reflective practice (Adams, Turns, and Atman 2003; Atman 2019; Atman et al. 2007). It has also been previously used by the research team to understand the job responsibilities of engineering, which supported seamless analysis due to the team's familiarity (Pollack, Sarrafian, and Grimm 2021)**.** The KAO to design process mapping was conducted through a collaborative coding process between the first and third authors who received an interrater reliability of 85% when applying the KAO. The KAO v. Design process mapping will be shared within the final section of the results.

4. Results

The KAO describes five cognitive actions that classify how designers apply knowledge in design. These actions will be termed knowledge actions throughout this paper, as they focused on the application of knowledge. The results of this paper are structured to provide a descriptive mapping of the research analysed in this literature review with the specific knowledge action that the research details. Each knowledge action will be defined and described in relation to the papers found to relate to this specific form of cognition.

4.1. Recognise

The first knowledge action to be described is Recognise. As defined above, Recognise is:

Table 2. Papers showing knowledge recognition as supported by cognitive structure.

Paper	Evidence of recognise
(Stompff, Smulders, and Henze 2016)	Surprises occur when the spontaneous recognition of the importance of a facet in a design problem is noticed and brought into the context of the design solution. The implementation of this facet triggers 'reframing processes, and consequently, is beneficial for team learning and innovation.'
(Dorst 2019)	Interpreting is a process of recognising, as it is the act of seeing the problem differently based on new information. The new information thus fortifies the knowledge structure amidst shifting and complex challenges.
(Liikkanen and Perttula 2009)	Implicit decomposition suggests there is a subconscious mechanism allowing designers to understand and decompose a problem, in the absence of deliberate analysis. The process highlights the tacit nature of recognising knowledge.
(Kahlon and Fujii 2022)	Their findings provided insight into how designers interpret the design space, internally, and how those interpretations map to the external world. This study indicates how a designer interprets a design space to implement structure internally.
(Kelly and Gero 2014)	This work demonstrates the internal movement of design situations during interpretations. The study shows how a designer's experience and connected knowledge determine how design spaces are interpreted within a design process.
(Lo et al. 2025)	Found that cognitive flexibility and cognitive empathy (perspective taking) both supported design thinking disposition. Being able to flexibly consider other perspectives supports informed and successful design processes.

> The action of seeing, noticing and perceiving information and its importance, due to the knowledge that is accessible within the practitioner's cognition.

This process is highly related to what knowledge a designer has and thus reflects the structure of a practitioner's cognition.

4.1.1. Recognising knowledge reflects cognitive structure

The process of recognising knowledge is not deliberate but depends on the accessible knowledge within a practitioner's cognition. Recognition is related to the cognitive mechanisms of perception. Several studies, summarised in Table 2, collectively illustrate that recognising knowledge involves leveraging a designer's cognitive structure and its flexibility to interpret, comprehend, and perceive importance within a design context.

4.1.2. Recognising knowledge is a process of analogical thinking

Analogical thinking is a mechanism that supports designers as they recognise knowledge, its importance and its application. The mechanism of analogical thinking occurs when information from a source concept inspires connection to a target topic. This can be found when previous experiences and expectations inform current tasks. Several studies have shed light on how analogical thinking plays a crucial role in recognising knowledge. Analogical thinking is widely studied in design because it draws on past experiences to shape interpretation, expectations, and decisions. The literature shows a strong link between analogical thinking and the recognition of knowledge; these findings are outlined in Table 3.

4.1.3. Affordances as a process of recognise

Affordances are potential actions offered to an individual by a designed artifact; affordances are the user's interpretation of a solution. Two papers in this review, see Table 4, investigated affordances, which are a key result of the cognitive action of recognising knowledge.

Table 3. Papers indicating recognise as an analogical thinking process.

Paper	Evidence of recognise
(Ball, Ormerod, and Morley 2004)	Experts can better recognise knowledge due to their organised knowledge structures. Their analogical reasoning turns into schema-driven design, which reflects how well-structured their knowledge is.
(Demian and Fruchter 2006)	When knowledge is recognised, having a contextual grounding of the knowledge is necessary for creating a connection to the designer's internal model. This opens a pathway for more thorough analogical application.
(Shergadwala et al. 2018)	When a designer is able to directly map their experiences and domain knowledge onto the design task, they apply closer analogical reasoning, allowing them to recognise a design problem more thoroughly to generate better solutions.
(Christensen and Ball 2016)	Drawing from unique background knowledge when developing analogies in teams facilitates communication between members, as it encourages re-visitation of analogies that link diverse domain knowledge.
(Casakin and Goldschmidt 1999)	Visual stimuli can be beneficial when prompting designers as they recognise knowledge. The stimuli can encourage focused recognition of aspects of a problem that are analogical to what they know.
(Lee and Ostwald 2024)	By investigating non-perceptual cognition (NPC), researchers investigate how designers 'see with their minds eye'. The study found that NPC events facilitate idea generation in individual design processes, confirming that concept retrieval is grounded in a practitioner's cognition, not just visual stimulus.
(Visser 1995)	Episodic data is one way to approach recognising knowledge as a form of analogical reasoning of case -based abstractions. Knowledge is recognised through recognition of episodes from either oneself or other people.

Table 4. Papers indicating recognition of affordances.

Paper	Evidence of recognise
(Stoffregen and Mantel 2015)	Affordances exhibit the ability of people to explore and recognise knowledge and the opportunity to leverage features of the design solution.
(Still and Dark 2013)	Affordances are aspects of perception, or the ability to recognise. This study investigates affordances through cognitive systems: long-term and working memory, automatic and controlled processing, and stimulus/response relationships. They find a consistent stimulus/response cycle as being crucial to recognising affordances.

Affordances emphasise recognition, as they occur when users perceive a function of a solution. These moments of insight arise from how knowledge is interconnected, enabling recognition.

4.1.4. Summary of recognize knowledge

The action of *Recognise* knowledge has been described in various ways in the literature, including through surprises, implicit decomposition, and problem interpretation and re-interpretation. These processes all rely on the knowledge structure a practitioner has developed to perceive the design space. Knowledge recognition is inherently implicit; using analogical thinking can connect internal understanding with external interpretation. Affordances and the process of perceiving opportunities share the same cognitive mechanisms as recognising knowledge, where the perception of opportunity and importance drives action.

Table 5. Papers on the process of gathering knowledge.

Paper	Connection to *Gather*
(Goldschmidt 2006)	Exploration of expansive design spaces allows designers to conduct on-the-spot experimentation to gather essential feedback on the design and the process.
(Studer et al. 2018)	A study of patterns of problem exploration derived 32 distinct patterns as examples of methods to gather information about the problem that is being investigated.
(Karlsson and Törlind 2016)	Knowledge acquisition through the whole design process was investigated to find different activities to inform the 'why', 'what' and 'how' aspects of a design space. Different activities are leveraged within different phases of a design project.
(Ahmed-Kristensen and Vianello 2015)	It is important for knowledge used within one phase of a design process to be transferred to other phases to ensure the designers gather the knowledge about what is learned from the implementation of previous designs.
(Dentsoras 2005)	The optimal approach to gathering information is to find the most important information with the least effort relatively early in the design process.
(Goudswaard et al. 2023)	Knowledge can be generated and gathered from prototyping. Different prototypes afforded the generation of knowledge of different domains.
(Chakrabarti, Morgenstern, and Knaab 2004)	The knowledge gathered throughout various phases of a design process impacts the requirements that guide the process.
(Lera, Cooper, and Powell 1984)	The information gathered is dependent on how the designer conceptualises their role related to the various aspects of the design problem that need to be addressed.
(Dong 2006)	Knowledge builds on knowledge, so when knowledge is gathered it is grounded upon the knowledge that is already present within the designer's mind.

4.2. Gather

The next knowledge action to be discussed is to *Gather* knowledge. This knowledge action is defined as:

> The action of acquiring information that is not already accessible within the designer's cognition.

The process and action of gathering knowledge has been highly studied within design research, as information acquisition is a necessary part of any design process. In this section, there will be a discussion of the various techniques of gathering knowledge and different structures that have been created to assist in gathering knowledge. Specific theories that highlight the importance of the acquisition of knowledge in design will be shared as well.

4.2.1. The process of gathering knowledge

As mentioned earlier, the action of gathering knowledge has been extensively studied. Often referred to as problem exploration, gathering knowledge occurs iteratively and throughout the design process. Significant research has been conducted to define how to approach gathering knowledge within design. This section highlights the key findings from these papers (see Table 5), to describe the process of how a designer gathers knowledge throughout design.

4.2.2. Gathering knowledge from other people

A key method of gathering information is seeking input from others. The transfer of information between colleagues and teams working on a project has been a significant area of research. Six papers explored the sharing of information within different types of design

Table 6. Papers indicating people to gather knowledge from.

Paper	Connection to *Gather*
(Loweth et al. 2021)	Provides an explicit definition of from whom knowledge is gathered , and a description of different patterns of gathering information behaviours in student teams.
(Culley 1999)	Different methods of gathering information from suppliers in the late 90s are outlined. These methods provide insight into how knowledge was gathered in design before easy access to the internet.
(Deken et al. 2012)	The patterns of knowledge sharing and seeking in consultation meetings were broken down to provide insight into how knowledge is gathered within novice and expert interactions.
(Aurisicchio, Bracewell, and Wallace 2010)	Design information is gathered from many different sources; however, informal face-to-face interactions are preferable.
(Tribelsky and Sacks 2010)	The approach of monitoring design processes by utilising the flow of information indicates the importance of gathering, sharing and disseminating knowledge within and between various teams of a design project.
(Vianello and Ahmed 2012)	Provides insight into how knowledge is shared within large design, construction and operation projects as either codified or personalised knowledge. The process of sharing indicates how knowledge becomes accessible to the receiving party.

projects, see Table 6. Knowledge sharing is a major advantage of collaborative work. These papers explore the various parties and reasons to seek, share, and communicate information within design projects.

4.2.3. *Categories of knowledge to gather*

Several research studies have worked to categorise the types of knowledge gathered within a design process. Some studies examine these categories through information request classifications. The distinctions between types of knowledge are crucial to structure how designers investigate problems. These categories, or ontologies of design knowledge, were developed for various purposes but offer valuable insight into the kinds of information that can be gathered during the design process. Different researchers have worked to categorise information essential for designers to gather within a project; these findings can be seen in Table 7.

4.2.4. *Summary of gather knowledge*

Gathering information is a very important part of the cognition of design. The literature review synthesised the categories in relation to how designers gather knowledge. First, knowledge was found to be gathered throughout the design process, gathering knowledge was found to impact the design process, just as the designer impacts what is gathered. Second, gathering knowledge was found to be a rather social process in which knowledge is shared among different people and parties within a design project. Finally, several categories of knowledge classification were found, which provided insight into the types of knowledge gathered within design. The cognitive action of gathering is important to how designers enact their knowledge within design.

4.3. *Use*

The process of *Use* knowledge is the action that allows the designer to make decisions and formulate solutions. It was defined as:

Table 7. Papers indicating categories of knowledge to gather.

Paper	Connection to *Gather*
(Willem 1988)	Defined design problem information as Function, Means or Accessory conditions information. Provides structure of the information gathered within design problems.
(Ahmed 2005)	Identified an index for knowledge reuse: process, product, function, and issue. System of categorisation allows design knowledge to be gathered and reused more easily.
(Xu, Ong, and Nee 2006)	A function-based design synthesis approach defined four facets of the product information models: Functional, Physical, Conceptual and Contextual. Provides insight into the type of important knowledge in product design from a functional standpoint.
(Deng, Tor, and Britton 2000)	Differentiated functional model knowledge using meta-level, physical level and geometric levels of design. Offers a perspective on the varied levels of detail of types of information that need to be accounted for and gathered in a design project.
(Damen and Toh 2022)	Investigated information to find 5 distinct information dimensions that designers perceive in their process. The research team finds that designers fluidly adapt their information usage according to their needs throughout the design process.
(Burleson et al. 2023)	Novice designer processes were analysed to understand what contextual factors are considered within design work. Participants frequently incorporated institutional and technological factors, but infrequently considered factors of infrastructure, industrial, economic, public health, environmental, socio-cultural and political contexts.
(Eastman, Bond, and Chase 1991)	The Engineering Data Model describes 5 structures to model engineering information. This imparts understanding of how engineering information is structured, thus informing how information can be gathered.
(Heisig et al. 2010)	Identified 69 needs categories within product lifecycles. These categories are the different types of information engineers need and gather within a product lifecycle.
(Aurisicchio, Bracewell, and Wallace 2013)	Classified six categories of information requests from aerospace engineers. The categories and sub-schemes of each describe the knowledge engineers intended to gather within their process.
(Hubka and Eder 1990)	Design knowledge was classified into 5 categories: design methodology, CAD, theory of design processes, theory of design object (technical systems), and special design knowledge. This structure classifies the categories of relevant information to encourage a more thorough acquisition of knowledge.
(Štorga, Andreasen, and Marjanović 2010)	Derived the Design Ontology, which offers a distinction of the complexity and characteristics of design knowledge that can be gathered within a design process.

The action of applying knowledge to analyze information, make decisions and construct logical arguments in a design space.

Many research initiatives that investigate the logic and decision-making behaviours within a design practice were found to describe this knowledge action. The studies highlighted in this section describe the way designers make decisions, both logical and illogical. This review will discuss overarching characteristics of reasoning in design as the complex cognitive process that relies on the knowledge action of use.

4.3.1. The subjectivity of using knowledge

The use of knowledge within design is as complex and diverse as the designers doing the design. As such, each designer is only able to leverage the information and structures they have access to within their unique cognition. This provides variety within how knowledge is used. Several studies within this literature review (Table 8) show the subjectivity embedded

Table 8. Papers indicating the subjectivity of using knowledge.

Paper	Connection to use
(Coyne and Snodgrass 1991)	Discussion of Hermeneutical philosophy shows that using knowledge in design to reason requires a level of subjectivity in order to truly understand the objectivity within the process.
(Dong and Heylighen 2018)	Investigated designer experts with autism to show that some neurodivergent experts use their knowledge differently than what is defined in research; however, their outcomes still exhibit good design.
(Peng and Miller 2023)	Preferences of creativity were investigated in relation to error detection in design decision making. The subjectivity of risk tolerance and motivation is shown to impact how decisions are made in design.

Table 9. Papers inducing defined processes of use.

Paper	Connection to use
(Kruger and Cross 2006)	Identified four cognitive strategies of experienced designers for approaching design: problem-driven, solution-driven, information-driven, and knowledge-driven. These strategies provide insight into how designers use their knowledge and understanding of what is important to make decisions .
(Ball and Christensen 2019)	Summarised the progress of the fields theoretical understanding of design cognition and metacognition, which describes how designers use their knowledge and how the use of knowledge is important for reframing ill-defined problems.
(Ahmed, Wallace, and Blessing 2003)	The use of knowledge within experienced designers' design tasks builds upon past situations, reasoning and intuition.
(Nickel, Duimering, and Hurst 2022)	Explored design space optimisation using set theory to identify 8 distinct trade-offs. These mechanisms show how designers conduct problem reformulation and reframing in a situation of decision trade-offs, and how designers negotiate using conflicting knowledge within a design space.
(Von Der Weth 1999)	Investigate how expert designers come up with good solutions early in the design process. Modelled how individuals use their knowledge about resources and experiences within the situation. It shows how designers use their knowledge within a design problem to develop ideas.
(Gish and Hansen 2013)	This paper shows that designers use knowledge by combining insights from previous projects to develop and justify new ideas based on the present constraints of a design problem.
(Wang et al. 2013)	This study provides insight into how knowledge is combined to create forward movement within a design problem and how dependencies describe the unique way in which designers use their knowledge.
(Le Masson, Hatchuel, and Weil 2016)	Using knowledge by splitting it up into smaller elements to encourage understanding assists designers to conduct generative design processes. This method is similar to how Bauhaus taught students how to use their knowledge within their design space.

in the act of using knowledge within design. These studies suggest that design reasoning is an incredibly unique process to each designer, as it reflects each individual's cognition.

4.3.2. Defined strategies of using knowledge

Knowledge was found to be used through specific strategies in design. The articles included in this review do not provide a comprehensive list of knowledge use strategies; rather, they provide a selection of potential strategies. This review acknowledges its limitations in describing knowledge use, while also acknowledging the expansive domain of cognitive actions that allow designers to use their knowledge to make decisions in design. The findings of the select strategies of using knowledge in design are shared in Table 9.

Table 10. Papers indicating reasoning patterns.

Paper	Connection to use
(Roozenburg 1993)	Patterns of reasoning in innovative processes indicate how knowledge is used within design. Knowledge is used through the process of innovative abduction to establish rules when reasoning between purpose and form.
(Galle 1996)	The different reasoning patterns within design provide insight into how designers use their knowledge to justify decisions with a process.
(Yang, Quan, and Zeng 2022)	Governing equations were defined to describe a designer's creative thinking processes used to approach the non-linear, chaotic, dynamic process of design. The equations can be solved and reformulated based on designers' creative capabilities and designers' knowledge and experience.
(Lee and Ostwald 2022)	The relationship between divergent thinking and ideation is quantified. Four distinct reasoning patterns are defined to describe the relationship between divergent thinking and ideation in design.

Table 11. Papers indicating the impact of problem information of use.

Paper	Connection to *Use*
(Christiaans and Van Andel 1993)	Designers make decisions regarding the direction of the product, based on the information provided to them. The knowledge presented in a design problem impacts the knowledge a designer will use within their problem solving.
(Vermillion et al. 2015)	The positive or negative framing of an outcome of a decision slightly impacts the risk attitude of engineers. However, the finding that engineers are typically risk-neutral provides insight into the objective decision-making tactics engineers take when using knowledge within design.
(Abi Akle, Yannou, and Minel 2019)	Not only the information, but also how the information is presented impacts the confidence in the use of knowledge by the designer.

4.3.3. Reasoning patterns within design

Specific reasoning patterns have been investigated in design. These reasoning patterns are grounded in the study of logic, and when applied within design they describe the logical (and sometimes illogical) approaches designers take to come to solutions. The exact pattern of logic applied within different stages of design is helpful to understand the different ways designers use their knowledge. See Table 10 for examples of reasoning patterns in design.

4.3.4. Problem information impacts the use of knowledge

In many cases, the knowledge presented in the design problem informs what knowledge is used within the process, which greatly impacts the way designers make decisions. Several studies in this literature review found evidence of this phenomenon (Table 11). The framing or the information provided to the designer within the design problem impacts how knowledge is used.

4.3.5. Design spaces in which to use knowledge

Several researchers have investigated the use of knowledge by projecting the process of design onto different design spaces. Design spaces provide conceptual models to describe the transformation of knowledge in design projects. Different projections of design space distinctions provide different conceptualizations of design, and thus different interpretations of using knowledge. Several design space configurations were found within this literature review, see Table 12, which provides insight into how knowledge is used and transformed within design.

Table 12. Papers indicating different design spaces to use knowledge within.

Paper	Connection to *Use*
(Rosenman and Gero 1998)	Knowledge from both socio-cultural and techno-physical regimes must be used within a design process to ensure the design is appropriately contextually aligned in purpose and function.
(Van Langen and Brazier 2006)	Provides insight into how designers reason, or use their knowledge, within the problem exploration phase of a design project.
(Hatchuel and Weil 2009)	Confirms the analytical and interpretive power of C-K theory by providing a sophisticated and nuanced description of the use of knowledge and concepts and their interaction within a design project.
(Taura and Nagai 2013)	The distinction between first and higher order generation provides insight into how and when inner sense becomes an important part of the designer's cognition.
(Wolmarans 2016)	The use of knowledge along the theoretical to material conceptualisation spectrum is important to ground design decisions into theory, while also being able to consider deep complexities of high semantic density.

Table 13. Papers discussing dual process theory.

Paper	Connection to *Use*
(Cash and Maier 2021)	This study investigates representations through gestures and sketching across various design phases. Findings contribute to how people use type 1 and type 2 processing while they create representations within their design project.
(Kannengiesser and Gero 2019)	Combines Dual Process theory and the FBS ontology to provide a mapping to develop a meaningful description of the cognitive actions taken while using knowledge within design.
(Lawrie et al. 2025)	Focuses on how Dual Process Theory interplays with existing design research. Insights into the aspects of design related to applying Dual Process Theory, namely the nature of the design problem, the designer and the practice of design are shared.

4.3.6. Dual process theory within design

Dual process theory has been developed to describe cognition as both fast/intuitive (illogical) and slow/deliberate (logical). Dual process theory was introduced in cognitive science to describe thinking patterns of humans; however, it has been studied in relation to design many times. Two studies within this literature review share insights about the use of knowledge through the lens of dual process theory, Table 13.

4.3.7. Summary of use knowledge

Overall, the use of knowledge in design is a complex activity that leverages many different aspects of a designer's cognition. This literature review found different strategies that describe the use of knowledge. Several studies defined explicit reasoning patterns, while others showed how the problem statement impacts the use of knowledge. A handful of different conceptual design spaces were defined to help explain the use of knowledge. Finally, several studies that leveraged dual process theory to describe the use of knowledge were presented. The section provides insight into how using knowledge occurs as the cognitive action of making decisions and constructing logical arguments within design.

4.4. Evaluate

The knowledge action of *Evaluate* was defined as:

Table 14. Paper indicating assumption checking in mental models.

Paper	Evidence of *Evaluate*
(Malak and Paredis 2007)	Model validation highlights the importance of being able to evaluate the representation of the design problem model when coming to a solution.
(Haroud et al. 1995)	Assumption evaluation informs the appropriateness of a design representation.
(McDonnell 2018)	Being able to organise knowledge into a meaningful frame and then continue to reflect and adjust the frame indicates the process of evaluating knowledge.
(Nielsen et al. 2025)	The process of reframing mitigates implicit and inaccurate assumptions when working on complex problems. Reframing and checking assumptions support tackling complex open-ended problems.
(Dixon and French 2020)	Theory suggests that questioning and gaining an understanding of something is an inherent process of design. Thus, suggesting that asking questions and gaining answers, or evaluating knowledge is a necessary part of design.
(Bell and Huang 1999)	Evaluating a knowledge structure for correctness has the potential to shift the designer's belief of what is known.
(Logan 1989)	Building external models of design spaces inherently includes the designers' biases, so it is necessary for the designer to be capable of evaluating the included abstractions and simplifications to ensure the models are appropriate.
(Nadler, Smith, and Frey 1989)	Provides evidence for the importance of evaluating the problem statement based upon the context in order to align the problem with the correct approach.

The ability for the designer to verify and validate knowledge and its application.

The process of Evaluation within the KAO involves aligning the internal and external components of the mental model. Within this literature review, several papers indicated how design researchers have investigated different aspects of how designers evaluate their knowledge.

4.4.1. Knowledge evaluation is a process of checking assumptions of one's mental model

As described previously, knowledge evaluation is the alignment of the internal mental model and the external representations. Several papers collected in this literature review state as much. Specifically, the process of checking a model, perception, or framing of a problem is necessary in order to ensure that the design solution meets the expected outcomes. Within this subsection, the importance of checking the validity of a model is presented (Table 14).

4.4.2. Iteration is prompted by knowledge evaluation

Designers were found to iteratively access knowledge, which allows designers to create meaningful solutions. Iteration was found to be linked to the knowledge action of evaluate, as evaluation of information can highlight instances of informational misalignment. This sub-section describes the link between the knowledge action of evaluate and the act of iteration (Table 15).

4.4.3. Summary of evaluate knowledge

Evaluating knowledge structures and mental models is necessary to ensure the internal perception aligns with the external representation. Several research initiatives showed different ways evaluation allows designers to align their internal and external representations

Table 15. Papers indicating iteration as a process of evaluate.

Paper	Evidence of *Evaluate*
(Waldron and Waldron 1988)	Continuous reflection on the alignment of previous experience and the current iteration of the task is necessary to let the solution develop. This reflection is a form of evaluation, as it verifies alignment of the task at hand.
(Cash, Gonçalves, and Dorst 2023)	Explains cognitively grounded co-evolution, which highlights the interplay of cognitive processes such as imagination, memory and understanding. Iterative principles of co-evolution are combined with metacognitive activities to describe the cognitive mechanisms working between problem and solution spaces.
(Cash and Kreye 2017)	The Uncertainty Driven Action (UDA) model links metacognitive uncertainty perceptions and cognitive processing. The model describes the inherent, iterative nature of the evaluation of uncertainty and shows how uncertainty perception evolves and balances between internal and external cognition.
(Cash and Kreye 2018)	Uncertainty perception is a driver of design activity progression. Perceiving states of uncertainty is a form of evaluation, as uncertainty occurs from a misalignment of the internal and external models.
(Jin and Chusilp 2006)	Different types of iteration are spurred by different ways of evaluating knowledge within design. This study describes how the presence of creative vs. routine design problems affects the mode in which internal evaluation occurs.
(Boudier et al. 2023)	Expert designers use iterative steps to transform initial ideas within evaluation processes. By defining six distinct thinking patterns, three roles are defined to describe how designers elaborate and transform different idea components.

of their design representation. It was also found that iteration is necessary within the evaluation of one's knowledge structure as it affords designers the ability to iterate and continue to evolve their design perceptions within uncertain contexts. Evaluating knowledge is an important part of informing one's design process, as it ensures the correct knowledge is applied at the appropriate time.

4.5. *Integrate*

The knowledge action of *Integrate* was defined above as:

> The action of assimilating knowledge into the designer's inherent cognitive processes. This consolidation develops design judgment, instinct, and intuition.

This knowledge action is the most mysterious, as the process of developing the sub and non-conscious cognitive processes is difficult to study. Nonetheless, several characteristics were found within this literature review that describe how previous research has investigated how knowledge is integrated into a practitioner's deep mental model to inform their design practices.

4.5.1. *The structure resulting from the integration of knowledge reflects the designer's unique perspective*

A first characteristic of the integration of knowledge is that the designer's unique perspective is inherently built into how their knowledge is integrated. Two papers showed how different aspects of designers' personalities are embedded in their design due to the way in which their knowledge is integrated, see Table 16. These studies indicate that design is an activity that requires each designer to access and combine their unique knowledge to create.

Table 16. Papers indicating the designer's perspective integrated into the cognitive structure.

Paper	Evidence of Integrate
(Sancar 1996)	The style embodied by a designer shows how designers have structured the knowledge and theories they build their practice upon.
(Newton 2004)	The process of design can be seen as a form of communication, where the designer discloses their understanding, creativity, and purpose through the designed artifact. This disclosure reflects how the designer's knowledge of the world is integrated into the conceptualisation of their work.

Table 17. Papers indicating cognitive order due to integration.

Paper	Evidence of integrate
(Cross and Cross 1998)	Framing is an example of externalising the integration of knowledge. The systematic view of the problem suggests the mental facilities that encourage order in design problems. The first principles, or the fundamental knowledge of a domain, are an example of base knowledge integrated into a practitioner's knowledge structure.
(Tang, Lee, and Chen 2012)	The practice of in-depth framing offers reflection on the strongly integrated internal knowledge structure. This typically leads to better overall performance within design.
(Björklund 2013)	The knowledge structures of expert designers are deep and detailed. This deep and detailed integration allows designers to perceive the interconnectedness of problem information and previous knowledge better.
(Song et al. 2019)	The study explores the relationships and intersections of design knowledge for a specific product. Findings show the interconnected and evolutionary nature of knowledge within a design space; this mimics the structure and dynamics of integrated knowledge of a practitioner.
(Popovic 2004)	Knowledge connection models provide a visual representation of how designers have integrated their knowledge. The paper shows the differences in organisation of mental representations for expert designers compared to novices.
(Brown 1996)	Knowledge compilation is a cognitive mechanism of knowledge integration. It describes the subtle changes in knowledge that allow problem solving to become more reflexive. Integration increases the speed of problem solving and bridges the gap between deep and surface level representations of design problems.
(Damen and Toh 2021)	This study delves into the ways experienced designers approach and organise information. There exist patterns for how designers structure information. This indicates that behaviours of integration may be similar between different designers.
(Shai and Reich 2004a, 2004b)	Infused Design is a form of knowledge integration, as it is a process that ensures the designer includes and infuses different and new knowledge together to support their design process.

4.5.2. Integrating knowledge creates order within the mental representation of a design scenario

The process of integration creates order within a designer's knowledge structure. Nine different papers within this literature review highlighted this finding (Table 17). These papers show how knowledge integration creates order within a practitioner's mental model to support and inform their process.

Table 18. Papers indicating examples of integration.

Paper	Act type	Evidence of *Integrate*
(Goldscmidt 1988)	Play and discovery	Knowledge is integrated into a stable structure through play and discovery.
(Mortati and Cautela 2025)	Data Thickening	Data thickenings are a proposed cognitive mechanism to allow greater organisation of data within a practitioner's cognitive process. Stages of contextualising, signifying, and grounding strengthen problem understanding and solution generation.
(Bucciarelli 2002)	Sketching	The designers integrate their knowledge from their internal representations into physical representations of their process to more easily communicate throughout their process.
(Römer, Leinert, and Sachse 2000)	Sketching	Sketching encourages designers to develop and articulate mental representations, thus supporting the process of integration with the benefit of external storage.
(Kokotovich 2008)	Mind-mapping	Building and explicitly connecting knowledge assists with the integration of knowledge. Building an organised structure of concepts within a process is useful. It allows novice designers to exhibit behaviours seen in experts.

4.5.3. Examples of the act of integration

This next section describes explicit examples of techniques to assist designers in integrating their knowledge. Four studies provided insight into several activities that allow for knowledge integration (Table 18). This list is not comprehensive of all the techniques that can assist designers in developing structure within their knowledge; however, it provides a useful starting point for future research on knowledge integration.

4.5.4. Summary of integrate knowledge

These studies provide insight into how different researchers have investigated the process of developing order in one's mental representations. The structuring and organisation of the mental representation and knowledge structures are the defining feature of the knowledge action Integrate. Knowledge integration is a necessary part of the cognitive ontology developed within this paper, as it is the process of consolidating and organising knowledge into a designers' inherent mental structure. It is a process that is unique to each designer, as their experiences and existing structures determine the way in which the knowledge is ordered. This section of the literature review highlighted key aspects of how to integrate knowledge and the impacts of a well-integrated knowledge structure.

4.6. Operationalising the KAO

The KAO was developed to provide insight into the various cognitive actions leveraged within the process of doing design. As suggested in the methods section, many of the papers analysed in this review presented multiple knowledge actions. Our analysis synthesised each paper to extract the core knowledge action to present a deeper interpretation of the characteristics of each action. However, in design practice, there are many stages, phases and tasks necessary to complete design tasks, each of which tends to overlap within the iterative nature of a design process. Thus, to interpret our results in relation to design cognition, we examined how the knowledge actions co-occur within a generic design process.

Table 19. The KAO vs. Design process.

		Recognise	Gather	Use	Evaluate	Integrate
Identification of Needs	Identify basic needs (purpose and reason for design)	x			x	
Problem Definition	Define what the problem really is, identify the constraints, identify the criteria, reread the problem statement or information sheets, and question the problem statement	x	x		x	x
Gathering Information	Search for and collect information		x			
Generating Ideas	Develop possible ideas for a solution, brainstorm, list different alternatives			x		
Modelling	Describe how to build an idea, including measurements, dimensions, and calculations		x	x		
Feasibility Analysis	Determine workability; does it meet constraints, criteria, etc.				x	
Evaluation	Compare alternatives, judge options, is one better, cheaper, or more accurate				x	
Decision	Select one idea or solution from among the alternatives			x	x	x
Communication	Communicate the design to others; write down a solution or instructions	x	x	x	x	x
Implementation	Produce or construct a physical device, product or system			x	x	x

Various classifications of design processes have allowed designers and researchers to better communicate the complex and convoluted nature of design activities, and by operationalising the KAO; it is possible to gather further insight into the characteristic cognition of each phase. This section provides a synthesis of the KAO with respect to design process activities to contribute a clear and novel perspective of design cognition. The results of the KAO vs. Design Process can be seen in Table 19.

From this brief comparison, it is possible to see how the KAO is a powerful tool to assist designers in understanding which knowledge actions should and can be enacted to approach a design process. This comparison also acts as an interpretive device to exemplify how the knowledge actions co-occur and support the incredibly complex cognition of design. The Knowledge Action Ontology contributes a clarifying scheme to bridge the gap between the knowledge of design practice and the cognitive actions leveraged within the practice. The KAO can assist designers in attending to the cognitive skills to develop, practice and tune to their processes to become more resilient designers.

5. Discussion

These five actions were derived from the literature set and are supported by existing, well-known concepts in design theory. Each knowledge action highlighted key aspects of the tasks in design. ***Recognise*** knowledge is highly connected to what Schön describes as problem setting or naming – defining what will be attended to and included in the frame of the problem (Schön 1983). This involves noticing and understanding what the problem is communicating. Our research highlights how the knowledge action of recognising allows designers to make connections between their existing knowledge and the external representations. ***Gather*** knowledge is critical, and a well-known cognitive action, due to its foundational role in design processes. The process of collecting information and bringing it into the design space is a common research topic (Bursic and Atman 1997), and as our findings show, has been widely studied from a myriad of angles. ***Use*** knowledge is known to be an important task, as once one has knowledge; it needs to be operated with, either through decisions, rationality, or logical argument (Jonassen 2012). Our research highlighted knowledge's connection to logic, and many other decision-making concepts. ***Evaluate*** was considered within the analysis from inspiration of Bloom's Taxonomy of learning objectives (Bloom et al. 1956; Krathwohl 2002). This knowledge action was found to align knowledge within the internal and external representations of a problem and to support the cognitive actions that allow iteration. ***Integrate*** knowledge was known to be important due to how related it is to developing expertise. When expertise is developed, knowledge is well-organised and easy to leverage within a design process, which inherently suggests the act of integrating knowledge into some existing cognitive structure of a designer (Cross and Cross 1998). These five actions comprise the Knowledge Action Ontology (KAO).

5.1. The KAO and memory constructs

The Knowledge Action Ontology (KAO) was created and designed to clarify how knowledge supports designers' cognition. As described in the background, many cognitive systems that allow humans to leverage their consciousness have been studied. However, these initiatives do not completely describe the actions that allow designers to acquire diverse information and synthesise such information into meaningful creations. The Knowledge Action Ontology is a construct to improve the design research community's comprehension of how knowledge builds the mental structure applied while solving a design problem.

To compare the KAO to the existing constructs of memory, a visualisation has been provided in which the knowledge actions are related to different memory processes. The visualisation in Figure 3 is intended to mimic a funnel in which the knowledge moves from an expansive state to a more intensive space. This figure exemplifies how designers are typically faced with a copious amount of knowledge, which is perceived with the Recognise action. The knowledge then moves through the layers of Gather, Use, and Evaluate to be grounded into a practitioner's cognition with Integrate.

The KAO conceptualises how designers interact with various memory processes, namely working memory, long-term memory, and subconscious. It should be noted, as introduced in the background section, that the memory constructs of working memory and long-term memory are known to be related, as working memory is an activated portion of long-term memory (Norman 1968). Thus, within our representation, it is important to understand that this relationship remains true. These memory constructs are interrelated, just as the knowledge actions are interrelated.

Recognise and *Gather* rely on working memory and require immediate and accessible knowledge to be enacted in their actions. *Use* works with both working memory and long-term memory, as it relies on both easily accessible, active knowledge as well as the stored knowledge that develops logical arguments. *Evaluate* leverages long-term memory due to its dependency on aligning with the stored memory systems; however, it also relies on the subconscious mechanisms of memory, in which deeper, nonconscious aspects of memory allow this knowledge action to interact with uncertainty. Finally, *Integrate* relates only to

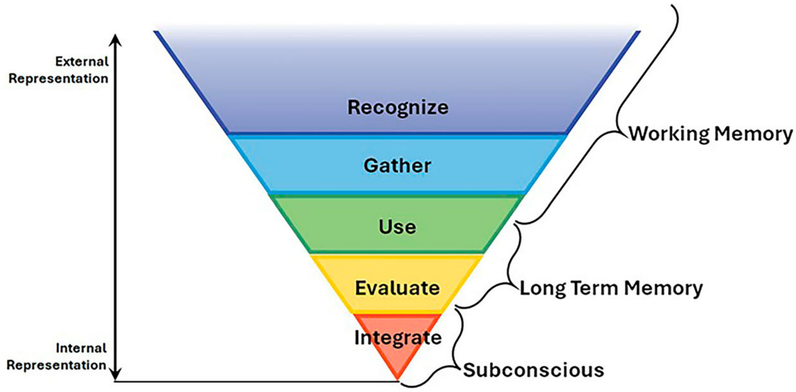

Figure 3. . Detail view of the knowledge action ontology.

the sub-conscious memory processes, in which instinct and judgement are interfaced with encouraging such structures to inform design practice.

Figure 2 has several other important visual cues that provide detail about the ontology's characteristics. The gradient in Recognise highlights the expansive nature of knowledge in design. Designers interact with vast quantities of knowledge, which can eventually be integrated into their existing structures.

5.2. Knowledge action and internal/external representations

One final aspect of the visualisation in Figure 3 is the aspect of internal and external representations. The internal and external representations relate to the mental models (Johnson-Laird 1983; Kirsh 2009) or knowledge structures of a designer's cognitive approach. Within the figure above, it shows how deeper knowledge actions relate to internal mental models, while higher actions deal with external information. Each knowledge action offers a dynamic relationship with respect to the other actions and with the levels of representation.

Starting from the deepest knowledge action, ***Integrate*** is the action related to the internal world; it allows new knowledge to assimilate, blend, and consolidate into existing mental structures, ensuring the designer's cognitive framework remains adaptable and cohesive. In the way that the knowledge action of *Integrate* is primarily related to the internal world and the structure of knowledge and cognition, the action of *Recognise* is primarily related to the external world and the structure of the external space. ***Recognise*** enables designers to perceive and make sense of the external environment based on their internal structures. It is limited by what a designer knows showcasing how external representations align with the existing integrated internal representations. ***Gather*** is the process that allows designers to encounter new information without fully integrating it. Gather allows designers to be reactive to the world as they explore the external world, informing their internal models without completely altering them. The information designers gather is directly related to what is recognised as relevant to the designer, which exhibits the interconnected nature of these knowledge actions. The ***Use*** action applies knowledge to construct solutions. This action begins to weave external information with the constructs of internal representations. The knowledge a designer uses is related to the existing concepts already possessed by them, as well as the new information gathered by the previous action. Use represents a designer's creativity, combining knowledge in innovative ways to address external problems. Finally, ***Evaluate*** ensures the internal and external worlds align, validating that a designer's conceptual solutions accurately represent reality. The subject of evaluation can be the outcome of any of the other knowledge actions, i.e. the recognisable perception, information gathered, reasoning used or integrated structure can be evaluated. Evaluate requires critical reflection on discrepancies between the internal representation and external context.

Together, these actions form a dynamic system in which designers continuously interact with and adapt their mental models to solve design problems. Naturally, and evidenced by the operationalising of the ontology, these knowledge actions co-occur within cognition. These actions are intended to define the basic building block of the cognition of knowledge application within design. Throughout this article, design has been considered as a complex, dynamic and iterative process. Thus, the knowledge actions, when analysed empirically, would be found to exist in a convoluted manner to support the dynamic cognition of a practitioner. There is evidence of this within our findings of how the KAO maps to the design process (Table 19). The purpose of this review was to untangle the overlapping cognitive threads to present a simplified cognitive classification for the future. The thematic characteristics of the actions are shared to define each action. However, cognition is complex, suggesting many of the thematic concepts can be applied across the different stages of design, as we showed above. The KAO provides a theoretical framework to better understand the complex cognitive behaviours involved in design. This ontology can serve as a research tool to explore how knowledge informs a design process.

5.3. Contributions

The **Knowledge Action Ontology (KAO)** outlines the cognitive actions that define how designers engage with knowledge throughout the design process. These actions – **Recognise**, **Gather**, **Use**, **Evaluate**, and **Integrate –** serve as the fundamental building blocks for complex cognitive mechanisms in design processes. Designers must cultivate and refine these skills to enhance creativity and innovation.

This ontology provides a framework to understand the relationship between these cognitive actions, helping researchers and practitioners navigate the nuanced and ambiguous nature of design thinking. The KAO creates a shared language for design researchers to discuss and study cognitive processes in design, offering a solid foundation for exploring the intricate mental tasks. In this paper, the definitions and descriptions of the KAO are presented in a clear and detailed manner. This presentation encourages researchers to continue design scholarship with the understanding of the core cognitive actions that enact knowledge within design practice. These core building blocks promote a cohesive understanding of the many approaches researchers have taken to uncover the cognition of designers. The organisation of papers can act as a catalogue for references regarding continued study of the characteristics of each knowledge action. The operationalisation of the KAO compared to the design process is an interpretation of the actions of the knowledge in design practice to support further work. The KAO is a conceptual synthesis of existing design work to create a shared language across the complex cognition of design to promote further work within design scholarship.

Further research could study exact patterns of knowledge-action co-occurrence within design practice. This would continue to formalise the ontology to solidify it as a theoretical model of design cognition. For example, a protocol analysis in which each knowledge action is analysed in parallel, similar to Atman's Design timelines (Atman 2019), could develop an exact model of the knowledge actions applied in design. Further examples of how to apply this ontology within practice include that the KAO could be implemented in a study design to prompt a participant to conduct particular actions within the experiment; this would provide researchers focused data to examine each knowledge action in a controlled manner. The research team applied the KAO in an empirical study to guide participants in a problem-exploration process to understand how each knowledge action impacted the development of the designer's mental models (Pollack, Myers, and Fu 2025).

By categorising and defining these cognitive actions, the KAO provides value to both the research community and design practitioners. It supports research by offering clear concepts and methods to study design cognition. It provides metacognitive tools for practitioners to reflect on and improve their design processes. Overall, the KAO enables the design community to describe, analyse, and understand the often-unseen cognitive phenomena that shape design work, paving the way for future research and meaningful insights into how humans approach design informed with knowledge.

6. Conclusion

This paper introduces The Knowledge Action Ontology. The KAO is a framework that outlines the cognitive actions that allow knowledge to inform design work. The ontology describes five actions that designers implement when working with knowledge in a design problem. The five elements of the ontology are Recognise, Gather, Use, Evaluate and Integrate.

Within this literature review it is shown that the different knowledge actions provide insight into the different behaviours seen within design work. *Recognise* is a process that reflects a practitioner's cognitive structure and is a process of analogical thinking that is informed by the knowledge with which the practitioner comes to the situation. *Gather* is the cognitive action that allows new information to be accessible to a practitioner to leverage within a process. Knowledge can be gathered from many different sources and can be categorised in many different schemes. *Use* is the cognitive action that allows designers to apply logic and reasoning in a design task. There have been various investigations regarding the patterns and enactments of using knowledge within various design spaces and contexts. *Evaluate* is the cognitive action that allows reflection and affords iteration; it is a process of verifying and validating knowledge. Finally, *Integrate* is the action that allows knowledge to be assimilated into a designer's inherent cognitive structure. This integration creates order within a practitioner's mental model and has been seen within several specific activities.

To further clarify how knowledge informs the cognition of design, the KAO is mapped onto an engineering design process. This mapping shows how the derived cognitive activities support and allow designers to apply knowledge within their design processes. A visualisation of the ontology was presented to instil grounding within memory constructs and internal/external representations of cognition.

These knowledge actions are skills that, when practiced, encourage resilient and flexible cognitive processes within design. The Knowledge Action Ontology is intended to provide grounded language to assist researchers studying design cognition. The KAO offers insight into the dynamic cognitive actions that inform the complex and open-ended process of design.

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