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Thoring, Katja; Mueller, Roland M.; Desmet, Pieter; Badke-Schaub, Petra

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Katja Thoring, Roland M. Mueller, Pieter M.A. Desmet, Petra Badke-Schaub

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Introduction

The design community has sought to define and analyze design knowledge for decades. Numerous authors have provided definitions, descriptions of characteristics, and frameworks of design knowledge. Much of today's seminal literature in the design discipline addresses questions about how designers think, learn, and acquire skills. [1] However, these sources tend to address the topic from different angles and to present their own terminology and definitions. At present, no unified model of design knowledge exists, as we illustrate through our extensive literature review in the next section.

Meanwhile, knowledge management today is still widely determined by a traditional business understanding that does not take into account the peculiar characteristics of design knowledge. [2] A lack of understanding about the different types of design knowledge—along with an ignorance of its requirements for knowledge transfer, knowledge creation, and other aspects of design knowledge management—can lead to a decline in a company's capability to innovate. This apparent gap in the knowledge between the two disciplines leads to our attempt to develop a comprehensive model of design knowledge—one that unifies the existing research from the design discipline and also takes into account the knowledge management perspective from the business discipline. Hence, our goal with this article is to develop a unified model of design knowledge that merges traditional knowledge management with the peculiarities of design knowledge. To do so, we first look at existing models for general knowledge, which mainly stem from knowledge management in the business discipline, to identify structures that could be adapted to develop a model for design knowledge.

Knowledge and Knowledge Management Models

After discussing some definitions of knowledge from a philosophical view, we compare several existing knowledge models from the knowledge management field.

Figure 1. SECI model of knowledge dimensions, based on Nonaka and Takeuchi.

Epistemological Understanding of Knowledge

Numerous theories and definitions are used to articulate what knowledge is. (For an overview, see the work of Ronald Maier. [3]) In the classical philosophical definition—as expressed in the Socratic dialog, "Theaetetus"—knowledge is described as "justified, true belief." [4] However, this definition is too narrow for our purposes because it excludes all knowledge that cannot easily be justified, such as gut feeling or design intuition. Another common approach is to make a distinction between knowledge, information, and data. For example, Agnar Aamodt and Mads Nygård use semiotics to differentiate between these three. [5] If a syntax regulates the correct combination of signs, we call this combination of signs data. Data need semantics to become information. If information is connected with other information, embedded in a context, and applicable to achieve a goal —which means it has a pragmatic dimension—it is called knowledge. Thus, knowledge provides the ability to perform effective decisions and actions. According to Patricia Alexander et al., the term knowledge refers to an individual's personal stock of information, skills, experiences, beliefs, and memories. [6] Gilbert Ryle differentiates between "know-what" (facts) and "know-how" (practical knowledge on how to accomplish something). [7]

Knowledge Models from the Knowledge Management Field

In the business discipline, various investigations, models, and developed knowledge management systems focus on the management of general knowledge. To develop a unified model of design knowledge, we look at four different existing models for general knowledge: (1) the SECI model, by Ikujiro Nonaka and Hirotaka Takeuchi; (2) the i-Space model (also known as the Boisot Cube model), by Max Boisot and Benita Cox; (3) the three-level model of human behavior, by Jens Rasmussen; and (4) the four-level systemtheoretic view of knowledge, by Franz Josef Radermacher.

Figure 2. i-Space model, or Boisot Cube, based on Boisot and Cox.

SECI Model. The SECI Model of Knowledge Dimensions, by Nonaka and Takeuchi, is one of the most established models of knowledge processing. [8] (See Figure 1.) The model differentiates between tacit knowledge and explicit knowledge. The letters S, E, C, and I stand for socialization, externalization, combination, and internalization, which describe the transition process between tacit and explicit knowledge.

i-Space Model. The i-Space Model by Boisot and Cox is a framework for knowledge management that focuses on three dimensions of knowledge. [9] (See Figure 2.) The first dimension establishes two types of knowledge: uncodified and codified. (They resemble tacit knowledge and explicit knowledge, respectively.) This dimension is the vertical axis of the three-dimensional cube. The shift between the two types occurs as codification (akin to externalization) and absorption (akin to internalization). In addition to the two knowledge types, the cube includes two knowledge quality dimensions: diffused and undiffused, knowledge, which is the degree to which knowledge is distributed; and a dimension distinguishing between abstract and concrete, which refers to the degree of transferability of knowledge from a general to a specific context and vice-versa. This distinction between concrete and abstract knowledge also is called situatedness in the literature. [10] The three-dimensional cube illustrates a social learning cycle, which takes place in a series of six steps.

Figure 3. Three-level model of human behavior, based on Rasmussen.

Rasmussen's Model of Human Behavior. The Rasmussen model asserts that human behavior can be skill-, rule-, or knowledge-based and that information is processed in different forms on these three levels: as signals, signs, or symbols, respectively. [11] (See Figure 3.) Skill-based behavior refers to automated behavior based on intuitive handling patterns that are difficult to verbalize. (Thus, it is similar to tacit knowledge.) Rule-based behavior refers to a more conscious action based on explicit rules (and thus is similar to explicit or codified knowledge). Knowledge-based behavior refers to human behavior in unknown or unfamiliar situations, where no previous rules or instructions guide the behavior. Behavior then is based on analysis of the situation and the creation of an appropriate action or solution. (The process is similar to problem-solving on a theoretical level.)

Radermacher's Knowledge Model. The four-level system-theoretic view of knowledge by Radermacher is based on a system-theoretic view of general knowledge processing, inspired by biological systems and evolution. [12] Radermacher's model uses a broad concept of knowledge, in which all patterns that enable actions or decisions are called knowledge. It differentiates between four levels of knowledge processing and three transitions between the four levels (see Figure 4). Level A, physical knowledge or "embodied knowledge," consists of the physical or signal level. The knowledge is expressed as a three-dimensional fit or a physical/chemical formation. One example is the immunological system, which works on the basis of a key/lock principle. The "knowledge" of the immunological system about past infections and the body's proper reaction is captured in the physical/chemical docking capability of an antibody with a virus. Level B, tacit or neuronal knowledge, uses neural networks, or "holistic methods," to process input. The knowledge is expressed as a (dynamic) equilibrium of activity levels in a neural network. [13] All sensorimotor knowledge that enables humans (and animals) to perform complex body movements (e.g., riding a bicycle) falls at this level. Level C (symbolic knowledge) represents knowledge expressed in the form of language, logic, and symbolic inference. A key for the performance of this level is the classification of world states in the form of concepts. This classification reduces the description complexity of a situation. Argumentation in the form of language, rule-based expert systems, and logic are placed at this level. These rules do not have to be based solely on one's own experience but also can be transferred from other organizations. Language can explain and justify these norms. Level D (scientific models) expresses knowledge in mathematical or scientific models or theories of the world. These four levels evolve one after the other and also are built up materially on each other. For example, a theory (level D) is based on explicit, codified knowledge (level C). Knowledge is represented at all levels through the construction and transformation of patterns. The representation of these patterns differs at each level.

Radermacher also addresses the transitions between these levels. Because our environment is overloaded with signals from the physical level, we need filters to select from all possible signals only the signals that are relevant for us. These filters also can be adjusted in the reverse direction to allow access to other signals for additional processing. Hence, knowledge representation can be transformed between level A and level B by filtering or adjusting filters. In the transition from level B to level C, a classification of world states and mental states into concepts capable of being expressed takes place. People agree on a common language, and tacit knowledge is externalized—for example, through codification and transformation into written or spoken language. As with the transition between A and B, this transition also proceeds in both directions: Moving from B to C, the tacit knowledge is codified and externalized (e.g., written down); moving from C to B, explicitly codified knowledge (e.g., traffic rules learned in driving school) can be internalized, such that they become autonomic or unconscious. [14] Finally, the transition between levels C and D describes the process of generating models and theories about the world. Knowledge from the previous level is being transformed into a framework, model, or theory. By moving downward, from level D to level C, a theory adds new concepts to the language (see Figure 4). [15]

Figure 4. Four-level system-theoretic view on knowledge, based on Radermacher.

In summary, none of the four models considered here explicitly addresses the specifics of design knowledge. Only Rademacher refers to a physical level of knowledge represented as three-dimensional forms, which is highly relevant to the design field. Boisot and Cox and Radermacher address the generation of new knowledge through knowledge transformations, which is supposed to be one of the key roles of designers. [16]

In the next section, we look at existing knowledge models from the design field.

Design Knowledge

We argue that the models discussed for the management of general knowledge do not address the specifics of design knowledge. Thus, what follows is a systematic literature search on existing theories and models about design knowledge. We searched the Scopus database with the search term, "design knowledge," to refer to design-specific information that is embedded in a context (e.g., intended use, goal, or briefing of an existing or envisioned design) and that hence enables designers to perform actions and decisions regarding their creations. The results were limited to the top design journals, as suggested by Gemser et al., [17] plus two more recent sources: *Design Science and The Journal of Design Creativity and Innovation*. The resulting 92 journal papers were filtered according to the following criteria: We focused on design knowledge taxonomies or classifications; we set aside work that used existing design knowledge categories (e.g., in empirical protocol analyses) that focused on only one specific type of design knowledge (e.g., tacit knowledge), or that presented knowledge-based systems (KBSs). We then reviewed the remaining 21 papers for backward and forward citation analysis, in which we also included works from other sources, such as books. This search process resulted in the 30 sources that we included in our literature review.

Our analysis of the 30 sources made evident that the amount of existing literature on the topic of design knowledge is large and manifold, indicating that this topic is important to the design community. However, the overview of concepts and terminology used regarding types and qualities of design knowledge reveals several problems:

1. *Lack of comprehensiveness*. Although several concepts are mentioned by different authors, creating several degrees of overlap, no comprehensive classification is offered.
2. *Redundancy.* Some works refer to several concepts that could be combined into one concept (e.g., intuition and implicit knowledge; abstraction and generalizability).
3. *Inconsistent terminology*. Many researchers seem to identify the same or similar concepts, but they use their own terminology. For example, object knowledge, artifact knowledge, and design precedents all refer to the same concept. When related concepts are given different names, discussing and relating the research streams becomes more difficult.

By clustering the presented concepts from the design literature thematically, we identified eight categories of knowledge types or knowledge qualities in the analyzed literature: (1) knowledge embodied in physical artifacts, (2) knowledge represented as tacit design intuition, (3) knowledge explicitly verbalized, (4) knowledge in the form of models or theories, (5) situated knowledge, (6) degrees of design expertise, (7) knowledge diffusion, and (8) knowledge content. We refer to the first four categories as knowledge types because they identify types of representation of design knowledge. The remaining four categories, which we call knowledge qualities, identify particular aspects of design knowledge that are somewhat orthogonal to the knowledge types. Some sources also address transformation of knowledge, which we illustrate as transitions between the knowledge types.

Table 1. Suggested Knowledge Types, Qualities, and Additional Concepts in the Analyzed Literature.

A Unified Model of Design Knowledge

With this article, we contribute a comprehensive model of design knowledge, which we've developed based on the 30 articles analyzed and the existing knowledge models. Our goal is for the design knowledge model to follow the structure from the knowledge management field, incorporating all identified categories from the design literature. We refer primarily to Radermacher's model as a foundation for developing our design knowledge model and we also rely on the i-Space model (Boisot Cube). The reasons for this decision are as follows:

1. The model by Rasmussen is similar in structure to the model by Radermacher, but it is less comprehensive, presenting only three levels instead of four. The fourth level suggested by Radermacher addresses the physical (artifact) level, which is crucial for the design discipline, in our view.
2. The SECI model by Nonaka and Takeuchi mainly focuses on two levels: tacit knowledge and explicit knowledge. They also emphasize the transformation of knowledge between these two states (externalization and internalization). These aspects are also present in Radermacher's model. The SECI model neglects the additional two levels of Radermacher's model.
3. Radermacher's model also addresses transitions between its four knowledge types. The transformation of one type of knowledge to another seems to be a necessary component in modeling knowledge and for generating new knowledge, which in our view is one of the main goals of design. The SECI model and the Boisot Cube also address such transitions, but both include only two knowledge types. Hence, the Radermacher model is more comprehensive.
4. The Boisot Cube combines its two knowledge types (codified and uncodified) with two knowledge qualities (diffused/undiffused and abstract/concrete). Although the model itself lacks comprehensiveness, we consider the combination of knowledge types and qualities a very promising approach and incorporate it into our model.

The following sections summarize the concepts found in the analyzed literature, which constitute the main categories of our proposed knowledge model.

Artifact Knowledge (Level A)

Design knowledge can be represented in physical artifacts. We call this level artifact knowledge. Nigel Cross uses embodied knowledge for knowledge about a specific handling, use, or function that is "frozen" in the physical form of an object. [18] To illustrate, the solution of how to open a bottle is inherent in the form of the bottle opener. Bionics offer another example: Certain properties of nature can be copied and transferred into designed products, just as the knowledge of the functioning of the botanic burdock is embodied in the designed shape of Velcro fasteners. Several papers refer to this type of design knowledge, although with different terms. For example, numerous authors use the term artifact knowledge. [19] Buthayna Hasan Eilouti, Rivka Oxman, and Brian Lawson refer to a similar concept using the term precedents. [20] Ezio Manzini and Joan Ernst Van Aken mention object knowledge. [21]

Design Intuition (Level B)

Adapting the level of tacit knowledge to design, we call this type of knowledge design intuition. The intuition of a designer for good (or bad) design is based on the neuronal level of design knowledge. Sometimes, designers cannot explain why a design is good or not— they just "know" because of their gut feeling. This intuition or tacit knowledge can be trained (e.g., through trial and error, through variations and test series, or just by experience). [22] Another possible way to build tacit knowledge is through observation and imitation. Neurological science has explained this process using the so-called mirror-neuron system. [23] When someone observes an action being performed, neurons in their brain fire as if they were performing the action themselves. Therefore, simply being in a relevant environment (e.g., an internship) and observing and working with an expert designer could lead to enhancing the design intuition.

This type of design knowledge is called intuition by some researchers, including Michel Benaroch, Donald Schön and Glenn Wiggins, and Raymond Willem. [24] Others use the terms talent or skill [25]; implicit knowledge [26]; or tacit knowledge. [27] Willem and Zdenek Zdrahal call it experience, [28] while Eilouti and Oxman refer to memory knowledge. [29] Lawson introduces the term body knowledge. [30] Cross refers to knowledge within people. [31] Although slight differences exist in the exact definitions, all of these terms describe a similar phenomenon: the internal or non-externalized representation of design knowledge.

Design Language (Level C)

We use the term design language to indicate the symbolic level of design-related knowledge. Symbolic design knowledge is codified as text, figures, and symbols. A specific design solution can be discussed by means of linguistic argumentation. This level also includes the different expression skills of a designer, such as visual languages (e.g., construction diagrams), sketching and (technical) drawing, specific design terminology, and the use of design software. This type of design knowledge (design language and terminology) is labeled in many papers as explicit knowledge. [32] However, we use the term design language instead to distinguish this type of design knowledge from general knowledge.

Design Theories (Level D)

Similar to Radermacher's "model level," involving testable theories, we call this level of knowledge design theories. A design theory or model constitutes design knowledge in a highly compressed and abstracted form. Typical design theories might involve ergonomic norms or patents, which can be tested, transferred to different projects, and adapted for specific purposes. Different design solutions based on one theory or model can later be tested and verified in other venues. For example, a chair that was designed based on ergonomic norms can be tested among people who represent a sample of the population's body masses. In addition, Christopher Alexander and colleagues introduced a set of patterns that are applicable to different design problems. [33] Herbert Alexander Simon argues that we need a science of design that is a "tough, analytic, partly formalizable, partly empirical, teachable doctrine." [34] Compared to a natural or behavioral theory, a design theory focuses on "how to do something" and gives "explicit prescriptions on how to design and develop an artefact." [35]

Design knowledge models or theories were suggested in a few of the analyzed sources. For example, Luz Maria Jimenez Narváez refers to empirical-analytical knowledge. [36] Eilouti refers to the concept of design patterns. [37] Kees Dorst and Isabelle Reymen mention the necessity of testable knowledge but do not specify what that might be. [38] Benaroch suggests logical arguments and proofs, which resemble testable theories. [39] To further investigate the concept of design theories, readers might look to Friedman and to Gregor and Jones, who describe the components of a design theory. [40]

Transition A–B

For the transition between Artifact Knowledge (Level A) and Design Intuition (Level B), we use Radermacher's terms: "filtering and adjusting filters." Signals from the physical level are filtered, or the designer's perception of the environment may be adjusted during this process. Designers are able to look at the world differently: They tend to see things (e.g., problems and opportunities) that other people don't notice.

Transition B–C

In the context of design, the tacit knowledge from Level B becomes externalized into codes and symbols. This codification might stem from the agreement on a design terminology, from the learning of design-specific expression skills (e.g., drawing or model-making), or from reflecting on previous tacit experiences and verbalizing and discussing them. [41] In the other direction, explicit knowledge can be internalized (trained) through frequent application.

Transition C–D

This transition describes the process of generating models and theories that might be relevant for the designer. Such models and theories might be influenced by, for example, user observations, a system analysis, or storytelling. Designers usually do not create general design "rules"; rather, they create practical models or frameworks intended for a specific design problem. Such design models could be causal graphs, "journey maps" that describe a process over time, "two-by-two" matrices, Venn diagrams that classify observations, or fictitious "personas." This transition resembles the "synthesis" step in the design process. [42]

In the analyzed literature, only a few authors suggest knowledge concepts that address a transition between different types of knowledge. Schön, Heylighen and colleagues, Cross, and Dorst mention the importance of reflecting on the results of trial and error, which we see as externalizing tacit knowledge. [43] Schön and Wiggins emphasize the importance of “a particular way of seeing” for design. [44] In addition, Lawson mentions the ability “to see or hear in particular ways.” [45] We interpret this move as the transition between the physical level (i.e., present signals from artifacts and environments) and tacit knowledge, in which one’s perception of this environment is being adjusted. In total, three transitions emerge between the four knowledge types.

<u>Situatedness</u>
This concept also is called transferability, context-relatedness, or generalizability in the analyzed literature. It describes the degree to which the knowledge is domain or context-specific or can be transferred to other contexts and situations. The scale ranges from situated knowledge (context-specific) to general knowledge (transferable to other situations). Ashton introduces the term general knowledge, which is also mentioned by Belkis Uluoğlu. [46]

<u>Level of Expertise</u>
The level of design expertise describes how experienced and versed designers are in their respective design field. [47] Design expertise ranges on a scale from low expertise (novice) to high expertise (expert) and can occur within each of the identified types of design knowledge. In the analyzed literature, the concept of design expertise occurs in Dreyfus and Dreyfus, Casakin and Goldschmidt, Lawson, and Cross. [48]

<u>Knowledge Diffusion</u>
Knowledge diffusion, a term mentioned by Paola Bertola and José Carlos Teixeira, refers to the extent of distribution and accessibility of the design knowledge for other people. [49] It can occur on a scale from low diffusion (e.g., accessible or distributed to only one person) to high diffusion (i.e., accessible or distributed to many people). Meanwhile, Uluoğlu refers to personal knowledge, which is possessed by only one individual. [50] Åman and colleagues also refer to individual and collective design knowledge, which correlates with the concept of knowledge diffusion. [51]

<u>Knowledge Content</u>
The dimension of knowledge content is expressed not on a scale but rather in various selective topics. Still, it can apply to any knowledge type. Knowledge about something can be embodied in an artifact or represented as intuitive knowledge; it can be explicit or manifested as a theory. For example, in the literature reviewed, the content of a design artifact often is described as knowledge about functional, behavioral, and structural characteristics (which is part of the FBS ontology). [52] Zdrahal mentions domain knowledge. [53] Several authors refer to process knowledge, or knowledge of how to do something. [54] Uluoğlu distinguishes between operative and directive knowledge (how to do something) and associative knowledge (know-how). [55] These two dimensions also are introduced by Åman and colleagues using the terms declarative knowledge and procedural knowledge, respectively. [56] Moreover, Åman and colleagues distinguish between two types of design knowledge content: technical knowledge (e.g., the working principles of a turbine) and human-centered knowledge (e.g., knowledge about symbolism, culture, and aesthetics).

Figure 5. Unified model of design knowledge.

Figure 5 presents our suggested unified model of design knowledge, which is structurally based on Radermacher's knowledge model and the Boisot Cube. In terms of content, our model is constructed based on the categories identified in the analyzed design literature.

Our suggested unified model of design knowledge includes four knowledge types (i.e., artifact knowledge, design intuition, design language, design theories), labeled as Levels A, B, C, and D. The three transitions between these levels indicate that knowledge is being transformed from one level to the next through filtering (A>B) and adjusting filters (B>A); through internalization of knowledge (C>B) and externalization of knowledge (B>C); and through theory formation (C>D) and concept creation based on theory (D>C). The four knowledge qualities that can be found in each type of design knowledge (i.e., situatedness, expertise, diffusion, content) are illustrated as additional orthogonal layers.

Discussion

The unified model of design knowledge presented in this article summarizes and consolidates the multitude of existing definitions and theories of design knowledge, and it extends them further by adding an additional perspective from the management discipline. The resulting framework provides implications for design practice, design theory, and design education.

Implications for Practice

Practitioners and companies might benefit from the suggested model in two ways. First, knowledge management and transfer play an important role in any design-related or innovative organization and therefore should be facilitated by an understanding of the different design knowledge types. Second, the model might guide the development of corporate knowledge management systems for design knowledge. Because innovation has emerged as an important success factor for companies, a tailored strategy for managing design knowledge is crucial, as are deliberate actions to generate new design knowledge.

Implications for Theory

The comprehensive framework might facilitate future research in the design field on several levels: First, the design artifact as a knowledge repository is an important asset for design and design research (Level A). However, publications about artifacts cannot involve the physical object itself. Hence, a systematic understanding of knowledge extraction possibilities and knowledge transfer into design language seems to be an important factor for design research. Second, the question of how expert designers see—their special way of seeing the world—might be a promising research question (Transition A-B). Third, how design experts gain their design intuition (Level B) and what distinguishes experts' and beginners' intuition in design are two questions that the framework highlights. Fourth, the presented model allows a systematic analysis of the role of precise design terminology for conceptualizing, and it provides a foundation for design critique (Level C). Fifth, the framework facilitates synthesizing the research process to develop design models and theories (Level D).

Implications for Teaching

The unified model of design knowledge may help design educators to better understand different types and qualities of design knowledge and to teach them more effectively to students. Each of the eight presented knowledge dimensions, as well as the three transitions between knowledge types, provide the potential for developing tailored exercises. A better understanding of knowledge characteristics and requirements also can result in more effective teachings strategies. It might enable design educators to analyze and systematically critique their own design exercises, as well as to design new ones, based on the requirements of the different types of design knowledge to be transferred.

Conclusion

In this article, we present a unified model of design knowledge. Based on an extensive literature review, we offer a framework comprising four different levels of design knowledge —design artifacts, design intuition, design language, and design theories—and the transitions between these levels. Additional elements in the model incorporate four qualities of design knowledge: expertise, diffusion, situatedness, and content. The model is based on two models of general knowledge processing —that of Radermacher and that of Boisot and Cox; we adapt these models to the specific properties of design knowledge. As a result, this article contributes to a better understanding of design knowledge for companies, researchers, and educators in the design field.

References

1 See, e.g., Richard Buchanan, "Design Research and the New Learning," Design Issues 17, no. 4 (Autumn 2001): 3–23; Nigel Cross, "Designerly Ways of Knowing: Design Discipline Versus Design Science," Design Issues 17, no. 3 (Summer 2001): 49–55, https://doi. org/10.1162/074793601750357196; Nigel Cross, Designerly Ways of Knowing (London: Springer, 2006); Bryan Lawson and Kees Dorst, Design Expertise (Oxford, UK; Architectural Press, 2009); and Donald A. Schön, The Reflective Practitioner: How Professionals Think in Action, 2nd ed (London: Routledge, 2017).

2 Younjoon Lee and Jaewoo Joo, "How a Design Executive Officer Can Craft an Organizational Culture," Design Management Journal 10, no. 1 (October 1, 2015): 50–61. https://doi. org/10.1111/dmj.12022

3 Ronald Maier, Knowledge Management Systems: Information and Communication Technologies for Knowledge Management (Berlin: Springer, 2004).

4 Plato, Theaetetus, trans. Benjamin Jowett (Adelaide: The University of Adelaide Library, 2008).

5 Agnar Aamodt and Mads Nygård, "Different Roles and Mutual Dependencies of Data, Information, and Knowledge—an AI Perspective on Their Integration," Data & Knowledge Engineering 16, no. 3 (1995): 191–222.

6 Patricia A. Alexander et al., "Coming to Terms: How Researchers in Learning and Literacy Talk about Knowledge," Review of Educational Research 61, no. 3 (1991): 315–43.

7 Gilbert Ryle, The Concept of Mind (London: Hutchinson University Library, 1949).

8 Ikujiro Nonaka and Hirotaka Takeuchi, The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation (Oxford: Oxford University Press, 1995).

9 Max Boisot and Benita Cox, "The I-Space: A Framework for Analyzing the Evolution of Social Computing," Technovation 19, no. 9 (1999): 525–36.

10 See, e.g., Philippa Ashton, "Transferring and Transforming Design Knowledge," in Proceedings of the Experiential Knowledge Conference (Hatfield: University of Hertfordshire, 2007), 1–9; and Silvia Gherardi, "Situated Knowledge and Situated Action: What Do Practice-Based Studies Promise?" in The SAGE Handbook of New Approaches in Management and Organization, ed. Daved Barry and Hans Hansen (Los Angeles: SAGE, 2008), 516–25.

11 Jens Rasmussen, "The Role of Hierarchical Knowledge Representation in Decision-making and System Management," IEEE Transactions on Systems, Man, and Cybernetics 15, no. 2 (March 1985): 234–43, https://doi.org/10.1109/TSMC. 1985.6313353; and Jens Rasmussen, "Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models," IEEE Transactions on Systems, Man, and Cybernetics 13, no. 3 (May 1983): 257–66. https://doi.org/10.1109/ TSMC.1983.6313160

12 Franz Josef Radermacher, "Cognition in Systems," Cybernetics and Systems 27, no. 1 (1996): 1–42.

13 For neural information processing, see Stuart J. Russell and Peter Norvig, Artificial Intelligence: A Modern Approach, Instructor's Solutions Manual (Upper Saddle River, NJ: Prentice Hall, 1995).

14 For codification and internalization of knowledge, see Ikujiro Nonaka, "A Dynamic Theory of Organizational Knowledge Creation," Organization Science 5 (1994): 14–37.

15 Radermacher, "Cognition in Systems."

16 See, e.g., Per Åman et al., "The Scope of Design Knowledge: Integrating the Technically Rational and Human-Centered Dimensions," Design Issues 33, no. 2 (Spring 2017): 58–69, https:// doi.org/10.1162/DESI_a_00439; and Stephanie Wilson and Lisa Zamberlan, "Design for an Unknown Future: Amplified Roles for Collaboration, New Design Knowledge, and Creativity," Design Issues 31, no. 2 (Spring 2015): 3–15, https://doi.org/10.1162/DESI_a_00318.

17 Gerda Gemser et al., "Quality Perceptions of Design Journals: The Design Scholars' Perspective," Design Studies 33, no. 1 (January 2012): 4–23.

18 Nigel Cross, "Expertise in Design: An Overview," Design Studies 25, no. 5 (2004): 427–41.

19 Cross, "Designerly Ways of Knowing" (2001); Cross, Designerly Ways of Knowing, (2006); Ken Friedman, "Creating Design Knowledge: From Research into Practice," in Proceedings of the International Conference on Design and Technology (Loughborough: Loughborough University, 2000); John S. Gero, "Design Prototypes: A Knowledge Representation Schema for Design," AI Magazine 11, no. 4 (1990), https://doi. org/10.1609/aimag.v11i4.854; Thomas R. Gruber and Daniel M. Russell, "Design Knowledge and Design Rationale: A Framework for Representation, Capture, and Use," Technical Report KSL 90-45 (Stanford, CA: Knowledge Systems Laboratory, Stanford University, 1991); Wim Muller and Gert Pasman, "Typology and the Organization of Design Knowledge," Design Studies 17, no. 2 (April 1996): 111–30, 694X(95)00030-U; Wenjuan Wang et al., "A Critical Realism View of Design Artefact Knowledge," Journal of Design Research 11, no. 3 (2013): 243–62, https://doi.org/10.1504/JDR.2013. 056591; and Min Yan, "Representing Design Knowledge as a Network of Function, Behavio ur and Structure," Design Studies 14, no. 3 (July 1993): 314–29, https://doi.org/10.1016/0142694X(93)80027-A.

20 Buthayna Hasan Eilouti, "Design Knowledge Recycling Using PrecedentBased Analysis and Synthesis Models," Design Studies 30, no. 4 (July 2009): 340–68, https://doi.org/10.1016/j. destud.2009.03.001; Rivka Oxman, "Prior Knowledge in Design: A Dynamic Knowledge-Based Model of Design and Creativity," Design Studies 11, no. 1 (1990): 17–28; and Bryan Lawson, What Designers Know (New York: Routledge, 2004). Knowledge in Contemporary Design Research," Design Issues 28, no. (Spring 2012): 61–71, https://doi. org/10.1162/DESI_a_00143; Michael Polanyi, The Tacit Dimension (Garden City: Doubleday, 1966); and Chris Rust, "Design Enquiry: Tacit Knowledge and Invention in Science," Design Issues 20, no. 4 (Autumn 2004): 76 85, https://doi. org/10.1162/0747936042311959.

21 Ezio Manzini, "New Design Knowledge," Design Studies 30, no. 1 (2009): 4–12; and Joan Ernst van Aken, "Valid Knowl edge for the Professional Design of Large and Complex Design Processes," Design Studies 26, no. 4 (July 2005): 379–404, https://doi.org/10.1016/j.destud.2004. 11.004.

22 Claudia Mareis, "The Epistemology of the Unspoken: On the Concept of Tacited. R. Wagner et al., Lecture Notes in Computer Science (Berlin: Springer, 2007), 884–94, https://doi.org/10.1007/978-3-540-74469-6_86.

23 See, e.g., Giacomo Rizzolatti and Laila Craighero, "The Mirror-Neuron System," Annual Review of Neuroscience 27 (2004): 169–92.

24 Michel Benaroch, "Roles of Design Knowledge in Knowledge-Based Systems," International Journal of Human Computer Studies 44, no. 5 (May 1996): 689–721, https://doi.org/10.1006/ ijhc.1996.0029; Donald A. Schön and Glenn Wiggins, "Kinds of Seeing and Their Functions in Designing," Design Studies 13, no. 2 (April 1992): 135–56, https://doi.org/10.1016/0142694X(92) 90268-F; and Raymond Willem, "On Knowing Design," Design Studies 9, no. 4 (October 1988): 223–28, https:// doi.org/10.1016/0142-694X(88)90007-5.

25 Hernan Casakin and Gabriela Goldschmidt, "Expertise and the Use of Visual Analogy: Implications for Design Education," Design Studies 20, no. 2 (March 1999): 153–75, https://doi. org/10.1016/S0142-694X(98)00032-5; and Ken Friedman, "Creating Design Knowledge: From Research into Practice," in Proceedings of the International Conference on Design and Technology (Loughborough: Loughborough University, 2000).

26 Benaroch, "Roles of Design Knowledge"; Kees Dorst, "The Problem of Design Problems," in Expertise in Design, ed. Nigel Cross and Ernest Edmonds (Sydney: Creativity and Cognition Studio Press, 2003), 135–47; and Rivka Oxman, "Educating the Designerly Thinker," Design Studies 20, no. 2 (1999): 105–22.

27 Åman et al., "The Scope of Design Knowledge"; and Donald A. Schön, "Designing: Rules, Types and Words," Design Studies 9, no. 3 (1988): 181–90.

28 Willem, "On Knowing Design"; and Zdenek Zdrahal, "The Role of Knowledge in Design Problems," in International Conference on Database and Expert Systems Applications (DEXA 2007),

29 Eilouti, "Design Knowledge Recycling"; and Oxman, "Prior Knowledge in Design."

30 Lawson, What Designers Know.

31 Cross, Designerly Ways of Knowing, 2006; and Cross, "Designerly Ways of Knowing," 2001.

32 Åman et al., "The Scope of Design Knowledge"; Ashton, "Transferring and Transforming Design Knowledge"; Benaroch, "Roles of Design Knowledge in Knowledge-Based Systems"; Oxman, "Educating the Designerly Thinker"; Schön, "Designing: Rules, Types and Words"; and Schön and Wiggins, "Kinds of Seeing and Their Functions in Designing."

33 Christopher Alexander et al., A Pattern Language: Towns, Buildings, Construction (New York: Oxford University Press, 1977).

34 Herbert Alexander Simon, The Sciences of the Artificial, 3rd ed. (Cambridge, MA: MIT Press, 1996), 113.

35 Shirley Gregor and David Jones, "The Anatomy of a Design Theory," Journal of the Association for Information Systems 8, no. 5 (2007): 313.

36 Luz Maria Jimenez Narváez, "Design's Own Knowledge," Design Issues 16, no. 1 (Spring 2000): 36–51.

37 Eilouti, "Design Knowledge Recycling."

38 Kees Dorst and Isabelle Reymen, "Levels of Expertise in Design Education," in Proceedings of the 2nd International Engineering and Product Design Education Conference, ed. P. Lloyd et al. (Delft, The Netherlands: Delft University of Technology, 2004), 159–66.

39 Benaroch, "Roles of Design Knowledge in Knowledge-Based Systems."

40 Ken Friedman, "Theory Construction in Design Research: Criteria: Approaches, and Methods," Design Studies 24, no. 6 (November 2003): 507–22, https://doi.org/10.1016/S0142-694X(03)00039-5; and Gregor and Jones, "The Anatomy of a Design Theory."

41 See Schön, The Reflective Practitioner.

42 Jon Kolko, Exposing the Magic of Design: A Practitioner's Guide to the Methods and Theory of Synthesis (New York: Oxford University Press, 2011).

43 See Schön, The Reflective Practitioner; Ann Heylighen et al., "Walking on a Thin Line—Between Passive Knowledge and Active Knowing of Components and Concepts in Architectural Design," Design Studies 20, no. 2 (1999): 211–35; Cross, "Designerly Ways of Knowing" (2001); and Dorst, "The Problem of Design Problems."

44 Schön and Wiggins, "Kinds of Seeing and Their Functions in Designing."

45 Lawson, What Designers Know.

46 Ashton, "Transferring and Transforming Design Knowledge"; and Belkis Uluoğlu, "Design Knowledge Communicated in Studio Critiques," Design Studies 21, no. 1 (January 2000): 33–58, https://doi.org/10.1016/S0142-694X(99)00002-2.

47 Lawson and Dorst, Design Expertise.

48 Stuart E. Dreyfus and Hubert L. Dreyfus, "A Five-Stage Model of the Mental Activities Involved in Directed Skill Acquisition," Operations Research Center (Berkeley, CA: University of California, 1980); Casakin and Goldschmidt, "Expertise and the Use of Visual Analogy"; Lawson, What Designers Know; and Cross, Designerly Ways of Knowing (2006).

49 Paola Bertola and José Carlos Teixeira, "Design as a Knowledge Agent: How Design as a Knowledge Process Is Embedded into Organizations to Foster Innovation," Design Studies 24, no. 2 (2003): 181–94.

50 Uluoğlu, "Design Knowledge Communicated in Studio Critiques."

51 Åman et al., "The Scope of Design Knowledge."

52 Gero, "Design Prototypes"; Gruber and Russell, "Design Knowledge and Design Rationale"; Wang et al., "A Critical Realism View"; and Yan, "Representing Design Knowledge."

53 Zdrahal, "The Role of Knowledge in Design Problems."

54 van Aken, "Valid Knowledge for the Professional Design"; Manzini, "New Design Knowledge"; Cross, "Designerly Ways of Knowing" (2001); and Cross, Designerly Ways of Knowing (2006).

55 Uluoğlu, "Design Knowledge Communicated in Studio Critiques."

56 Åman et al., "The Scope of Design Knowledge."

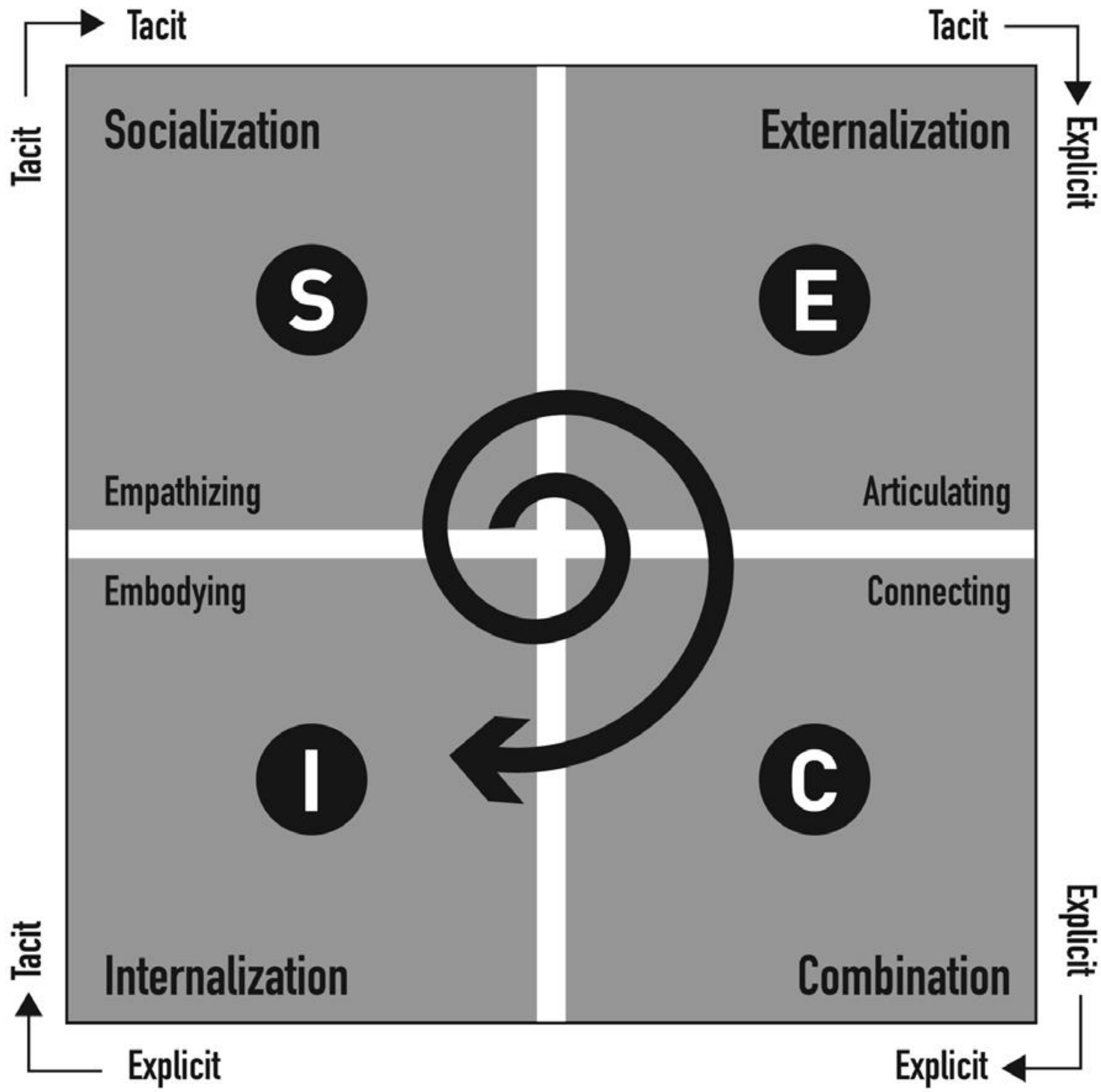

Tacit
Tacit
Tacit
Explicit
Socialization
Externalization
S
E
Empathizing
Articulating
Embodying
Connecting
I
C
Internalization
Combination
Tacit
Explicit
Explicit
Explicit

FIGURE 1

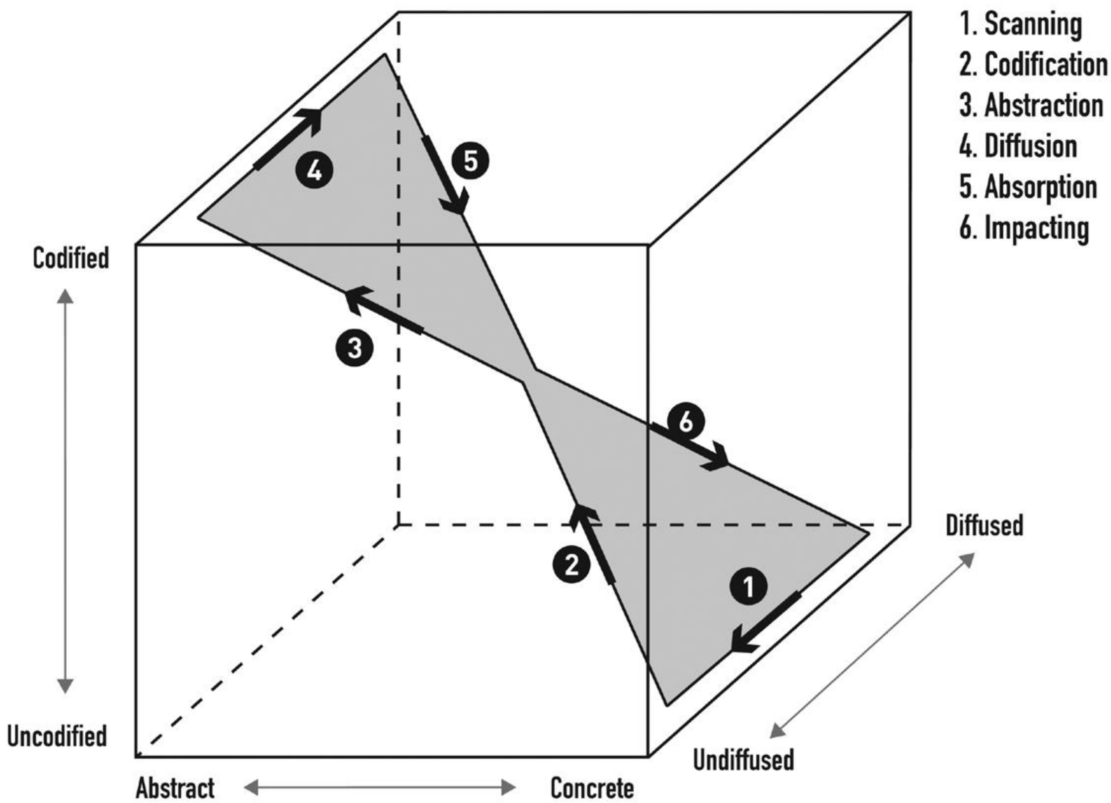
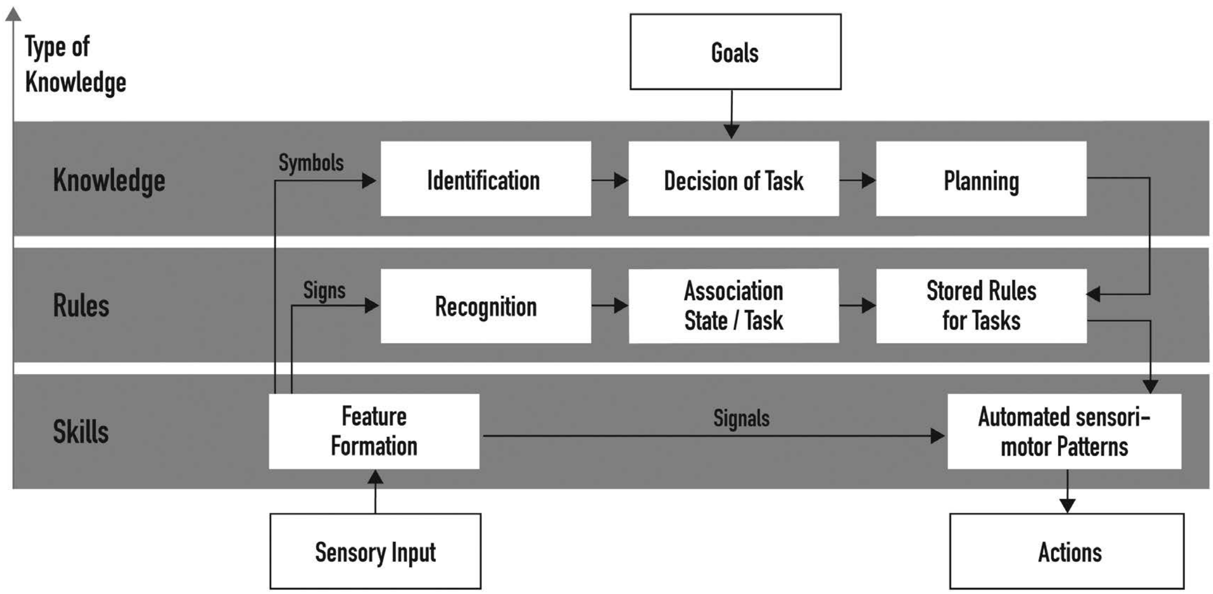

1. Scanning
2. Codification
3. Abstraction
4. Diffusion
5. Absorption
6. Impacting
Codified
Uncodified
Abstract
Concrete
Diffused
Undiffused
1
2
3
4
5
6

FIGURE 2



Type of Knowledge
Goals
Knowledge
Symbols
Identification
Decision of Task
Planning
Rules
Signs
Recognition
Association State / Task
Stored Rules for Tasks
Skills
Feature Formation
Signals
Automated sensori-motor Patterns
Sensory Input
Actions

FIGURE 3

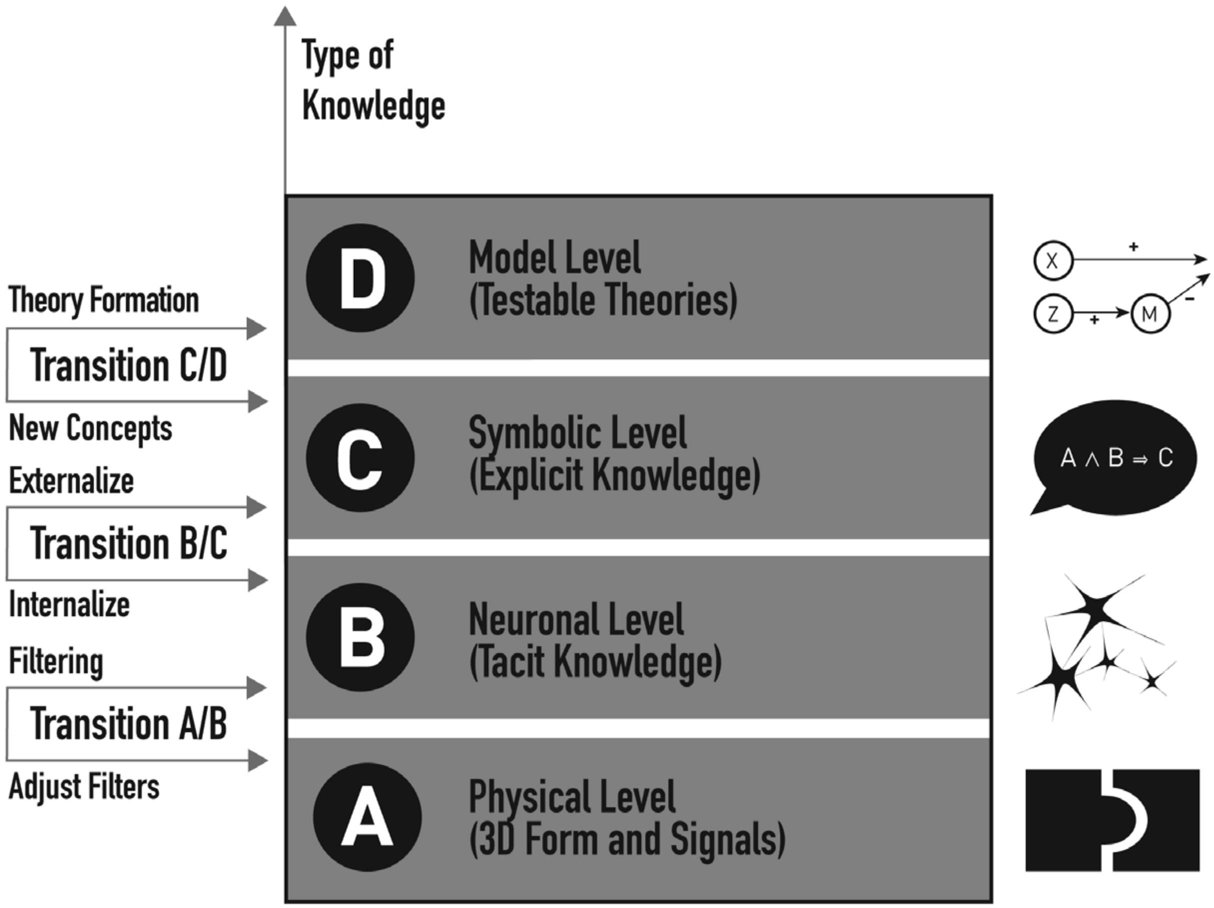

Type of
Knowledge
Theory Formation
Transition C/D
New Concepts
Externalize
Transition B/C
Internalize
Filtering
Transition A/B
Adjust Filters
D
Model Level
(Testable Theories)
C
Symbolic Level
(Explicit Knowledge)
B
Neuronal Level
(Tacit Knowledge)
A
Physical Level
(3D Form and Signals)
X
Z
M
A ∧ B ⇒ C

FIGURE 4

Table 1 | Suggested Knowledge Types, Qualities, and Additional Concepts in the Analyzed Literature

Reference	Design Artifacts	Design Intuition	Design Language	Design Theories	Transitions	Situatedness	Diffusion	Expertise	Content
Åman et al.		x	x				x		x
Ashton		x	x			x			
Benaroch		x	x	x					
Bertola and Teixeira							x		
Casakin and Goldschmidt		x						x	
Cross, 2006	x	x	x					x	x
Cross, 2001	x	x			x				x
Dorst and Reymen				x				x	
Dorst		x	x		x	x		x	
Dreyfus and Dreyfus		x						x	
Eilouti	x	x		x					
Friedman, 2000	x								x
Gero	x								x
Gruber and Russel	x								x
Heylighen et al.			x		x				
Lawson	x	x	x		x			x	
Manzini	x								x
Muller and Pasman	x								x
Narváez			x	x					x
Oxman, 1999		x	x		x				
Oxman, 1990	x	x				x			
Schön, 2017					x				
Schön, 1988		x	x						
Schön and Wiggins		x	x		x				
Uluoğlu					x	x	x		x
Van Aken	x								x
Wang et al.	x								x
Willem		x							
Yan	x								x
Zdrahal		x							x

TABLE 1

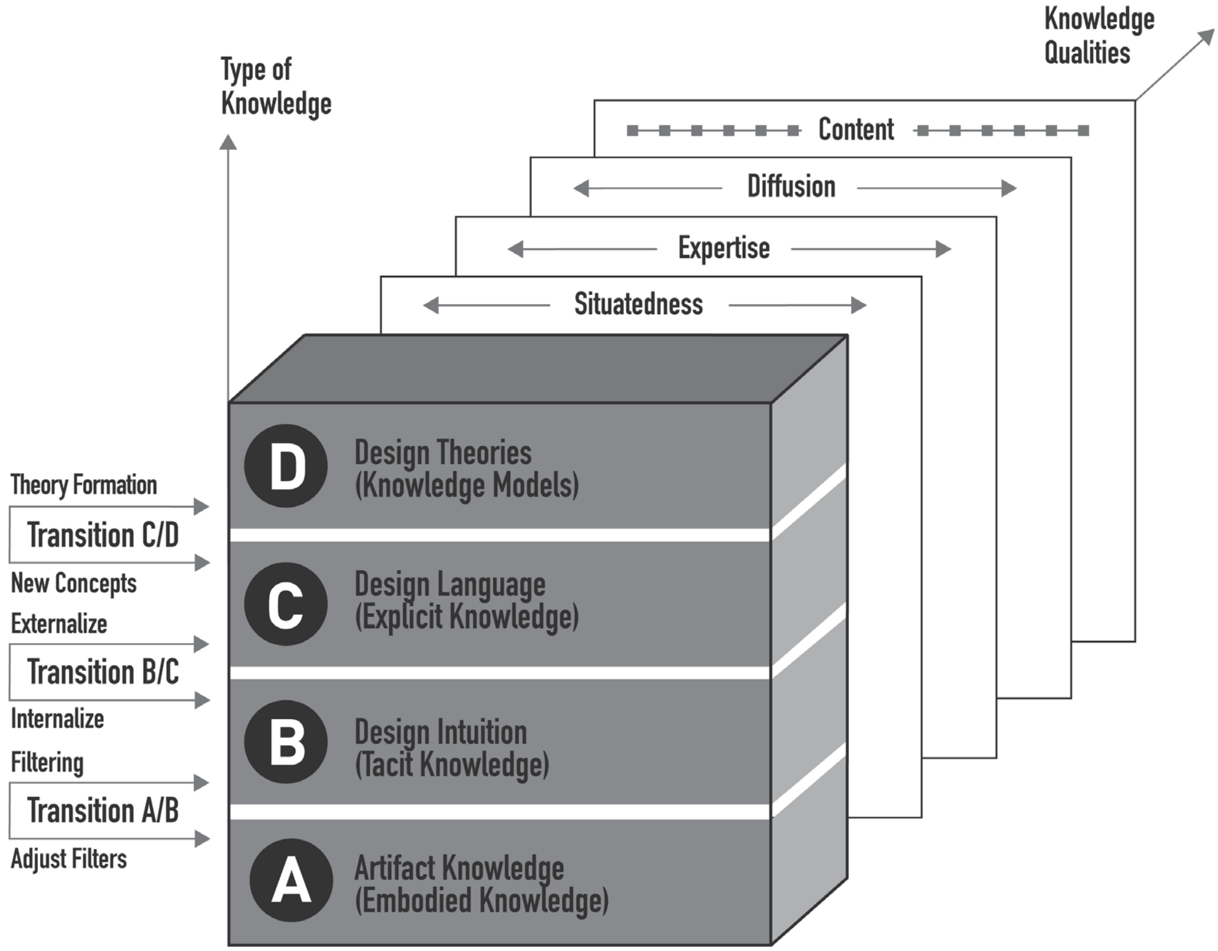

Knowledge
Qualities
Type of
Knowledge
Content
Diffusion
Expertise
Situatedness
D
Design Theories
(Knowledge Models)
C
Design Language
(Explicit Knowledge)
B
Design Intuition
(Tacit Knowledge)
A
Artifact Knowledge
(Embodied Knowledge)
Theory Formation
Transition C/D
New Concepts
Externalize
Transition B/C
Internalize
Filtering
Transition A/B
Adjust Filters

FIGURE 5