Designing for Knowledge Construction to Facilitate the Uptake of Open Science: Laying out the Design Space

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The uptake of open science resources needs knowledge construction on the side of the readers/receivers of scientific content. The design of technologies surrounding open science resources can facilitate such knowledge construction, but this has not been investigated. To do so, we first conducted a scoping review of literature, from which we draw design heuristics for knowledge construction in digital environments. Subsequently, we grouped the underlying technological functionalities into three design categories: i) structuring and supporting collaboration, ii) supporting the learning process, and iii) structuring, visualising and navigating (learning) content. Finally, we mapped the design categories and associated design heuristics to core components of popular open science platforms. This mapping constitutes a design space (design implications), which informs researchers and designers in the HCI community about suitable functionalities for supporting knowledge construction in existing or new digital open science platforms.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**.

Additional Key Words and Phrases: open science, knowledge construction, design implications, platform design

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1 INTRODUCTION

There has been a growing interest in the field of human-computer interaction (HCI) in designing and developing technology to support the uptake of open science resources through technology [21, 26, 28, 70, 73, 74]. Vicente-Saez and Martinez-Fuentes define open science [93] as *"transparent and accessible knowledge that is shared and developed through collaborative networks"*. In recent years, open science has become increasingly important as scientific knowledge is a crucial resource for increasing societal as well as economic growth [27]. Open science aims at removing barriers to access and re-use of research outputs. Fundamental principles in open science are that the scientific process and results should be transparent, reproducible, accessible, and shared. A widely known open science practice is open access publication, i.e., scientific publications free of cost for the readers. Another example of open science practice is the preregistration of studies that allows a time-stamped recording of a study design before the data collection and analysis are conducted [75]. Open science means to make research outcomes available in new ways (freely available to public, available in standard formats) and means to make new types of research outcomes available (process descriptions, fine granular data). These resources can be benefited if the information is understood and integrated into existing knowledge, i.e., knowledge construction processes must take place [50]. Knowledge construction is typically understood as an individual, cognitive, and collaborative, social process (ibid). In the present paper, we ask how these two processes can be supported with technology design in the context of open science.

This question is new in HCI, although others have already investigated open science from HCI perspectives in a more general sense. For example, Echtler and Häußler [21] analysed the entire body of papers from CHI 2016 and CHI 2017 regarding open source releases. They showed that only 2.3% released open-source code to the public. Rajanen and Iivari [74] postulate that politics are important in open source software usability design, as usability practitioners and researchers may need to employ lobbying strategies to be successful. Feger et al. [26] examined the requirements for technologies to support reproducible research. They postulate that HCI should take an active role in understanding, supporting and motivating reproducible practices. Open data has been studied in HCI from the perspective of exploring definitions or barriers in government and industry settings [70]. We, therefore, see that understanding open science practices and the role that technology plays in supporting or hindering the usage and uptake of open science artefacts is of interest to HCI. However, there is little systematic application of design knowledge available in HCI to the domain of open science [73].

It is precisely in this gap that our research is situated: Our goal has been to understand which design knowledge that could facilitate the uptake and success of open science is available within HCI. We have taken a learning perspective towards open science as a particular perspective. That means that we start from the perspective that the uptake of open science resources needs knowledge construction on the side of the readers/receivers of scientific content. An underlying assumption is that knowledge construction in open science is not per se different from knowledge construction in other contexts, for example, in learning environments. Therefore, we argue that designs used to support knowledge construction in other contexts can be drawn upon when designing for open science. However, any transfer between contexts, which ultimately means transfer between different socio-technical systems, must be done with care. In this work, we want to lay a solid foundation for such a transfer.

2 METHODOLOGY

Our methodology consists of two major parts: an analysis of literature (Part 1), and a synthesis of existing, empirically-based knowledge as found in literature into design implications (Part 2) for knowledge construction in open science. The overall methodology including detailed steps are depicted in Figure 1. Below, we describe the steps in the overall methodology, referring to this figure and step numbers as given there, and referring to the section of this paper where the corresponding results are described.

Part 1: We have analysed existing literature in two steps. Firstly, we have summarised existing literature on knowledge construction and synthesised it into a *combined model of knowledge construction* as theoretical background for our work (Step 1.1 and Step 1.2, Section 3). This literature does not address technology design, but cognitive and social processes. Taking this further, our aim was to collect and analyse design-oriented literature to explore how individual and collaborative knowledge construction can be supported through technology design (Step 2.1, Section 4). We have therefore carried out a scoping review that *"map[s]' relevant literature in the field of interest"* and *"address[es] broader topics"* [4].

To achieve this, we performed two search processes in Google Scholar [84] and ACM [55]. In the first search, we used the following search terms: "knowledge construction", "knowledge building", "open science", "open access", "open data", "learning", "information retrieval", and "search". In the second search, we focused on individual knowledge construction as only a single paper on this was found in the first round, and search terms were informed by results from the first search. We used the following search terms: "individual knowledge construction", "online", "adaptive technologies", "intelligent tutors", "tagging", and "online learning environment".Note that overall we found only one paper specific to knowledge construction in open science [57]. An immediate conclusion is that designing for knowledge construction in the context of open science has not yet been widely studied in HCI. In our work, we try to establish that HCI and related fields of research have substantial knowledge and ideas that can be built upon to inform the design of open science in terms of knowledge construction. In total we included $n = 30$ publications to the review. Details on the search processes, including inclusion criteria and rationale for search terms, are documented in the Supplementary Material.

In Section 4, we have summarised the retrieved papers and divided them into subsections according to their focus on either individual or collaborative knowledge construction, or both. From the retrieved papers, we have extracted *design heuristics* (Step 2.2, Section 4). By design heuristics we understand empirically substantiated guidelines on how knowledge construction can be designed for. Finally, we have also connected design heuristics back to knowledge construction theory by mapping them to levels of (individual and collaborative) knowledge construction.

Part 2: In the second part of our methodology, our goal was to develop these design heuristics into a design space for supporting knowledge construction in open science (Section 5). In this synthesis, we have again taken two steps. Firstly, we have reflected on the collected design heuristics and the technological functionalities that underlie them. We have grouped these functionalities into categories of technological functionalities, which we call *design categories* (Step 3, Section 5.1). On the one hand, the categories are connected to the combined knowledge construction model, and on the other hand, to HCI-related research communities that research on such technological functionalities. The design categories are useful for moving beyond the design heuristics, for which there is empirical evidence that associated technological functionalities support knowledge construction, towards larger spaces of technological functionalities for which there is no specific evidence that they support knowledge construction.

Secondly, we have reviewed popular open science platforms and identified the standard core components of multiple platforms (Step 4.1 and 4.2, Section 5.2). We then discussed which technical functionalities that support knowledge construction could be assigned to which core components.

The result of this discussion is a mapping of design categories and associated design heuristics onto these core components (Step 5, Section 5.2). Finally, this mapping results in a set of *design implications*, by which we mean suggestions for the design of knowledge construction in open science platforms. These design implications are based on i) knowledge construction theory, ii) knowledge about designing for knowledge construction (design heuristics) in other contexts, and iii) knowledge about typical open science platforms.

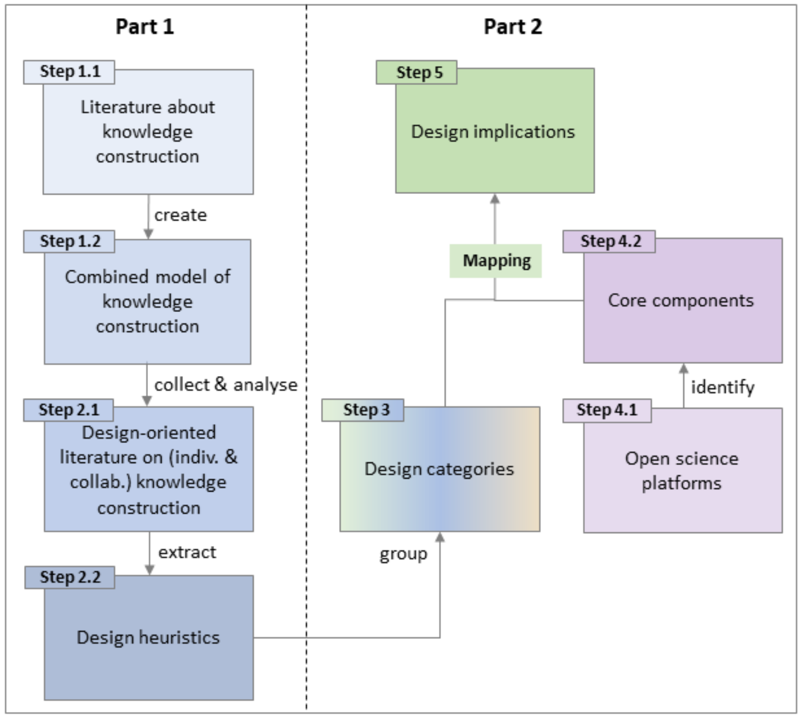

Fig. 1. Overall Methodology.

3 BACKGROUND: KNOWLEDGE CONSTRUCTION

Knowledge construction is described as a process of constructing new knowledge based on existing knowledge [92]. It can be considered from individual, cognitive or social, collaborative perspectives.

To construct new knowledge on an individual level, new information must be integrated, reflected and consolidated. Individual knowledge construction is often derived from constructivism [11, 15, 66, 92]. In this regard, knowledge is constructed based on previous knowledge and new concepts are formed and integrated into existing knowledge [94]. Cognitive individual processes of knowledge construction, called cognitive engagement, are described in the model of Dole and Sinatra [17] and consists of five levels that build on one another. Level (I): Simple processing of information; Level (II): Assimilation - assessing the extent to which information fits with previous knowledge; Level (III): Deeper Processing or reflection - attempting to make meaningful connections of new information to existing concepts through reflection and internal question; Level (IV): Reconstruction of previous knowledge concepts - new information can be integrated into existing concepts; Level (V): Meta-cognitive level - meta-concepts are created, which combine the new information with existing concepts. Information is consolidated into knowledge, and existing concepts are expanded when reaching all levels.

Research on collaborative knowledge construction indicates that externalisation of information and consensus building is often enabled by a conflict or dissonance of ideas, followed by the integration and co-construction of ideas, resulting in newly created knowledge [29, 35, 40, 88]. The model by Fischer et al. [29] describes collaborative knowledge construction along with four processes: 1) externalisation of task-relevant knowledge; 2) elicitation of task-relevant knowledge; 3) conflict-oriented consensus building, and 4) integration-oriented consensus building.

Stahl [88] provides a model for collaborative or social knowledge construction that presents a cycle of different influencing factors. In addition to reasoning, shared understanding, cultural artefacts and public explanations, he also includes personal understanding factors such as personal understanding, tacit prior understanding and personal belief.

The best known and most cited model regarding collaborative knowledge construction is the Interaction Analysis Model of Gunawardena et al. [35]. The model describes the process of knowledge construction consisting of five levels. Level (I): Sharing/comparing of information; Level (II): Discovery/exploration of dissonance or inconsistency among ideas, concepts, or statements of different participants; Level (III): Negotiation of meaning and/or co-construction of knowledge; Level (IV): Testing and modification of proposed synthesis or co-construction; Level (V): Phrasing of agreement, statement(s), and applications of the newly constructed meaning.

The co-evolution model by Cress and Kimmerle [15, 47, 50] brings collaborative and individual knowledge construction together. The model's core components are the social system, which promotes knowledge construction through communication, and the cognitive system, which promotes learning through cognitive processes. The social and cognitive systems are mutually dependent and enrich each other through information externalisation and internalisation. Externalisation describes the process of externalising knowledge by explicitly presenting and sharing information that reflects one's knowledge [15]. Based upon the model of Piaget [71], which describes learning internalisation of external information, Cress and Kimmerle [15] specify internalisation as an assimilation and accommodation process. In assimilation, information is added to previous knowledge. In accommodation, prior knowledge is adapted to new information. For example, existing knowledge is rearranged, organised or redefined to make new information integrable. Thus, learning is not only about learning new facts but also about adapting and adjusting cognitive structures.

Further, Scardamalia and Bereiter [79–83] have worked on related concepts under the name of "knowledge building". The developed theory focuses on building (≈ constructing), testing and adapting knowledge. While elements of this theory are connected to concepts of knowledge construction, knowledge building theory emphasises other aspects of learning than knowledge construction theories. Therefore, we don't build our work directly on the theory of knowledge building. Still, we have included the term knowledge building in our literature search because of its prevalence especially in literature on collaborative learning.

In our present work, we bring together collaborative and individual knowledge construction levels by combining three models as depicted in Figure 2. The core of our model consists of the co-evolution model by Cress and Kimmerle, and Kimmerle et al. [15, 47, 50] (see Fig. 2, in the middle). We extend this model (ibid) by specifying the collaborative and individual knowledge construction processes. We enhance the collaborative part (= the social system of [50]) with the five levels proposed by Gunawardena et al. [35], to specify the levels for collaborative knowledge construction (see Fig. 2, left). Further, we enhance the individual part (= the cognitive system [50]) with the five levels presented by Dole and Sinatra.[17] (see Fig. 2, right) to describe individual cognitive processes more precisely. We use this combination of models as the guideline to structure our scoping review and outline which levels of individual or collaborative knowledge construction could be achieved with technological support.

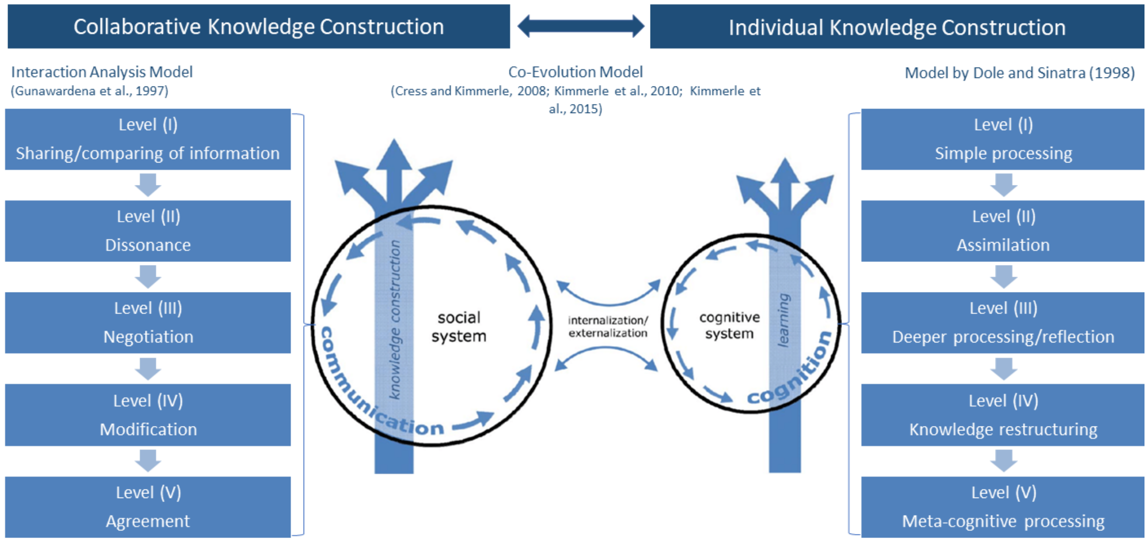

Fig. 2. Model for Collaborative and Individual Knowledge Construction as Guideline for the Scoping Review.

4 RESULTS: KNOWLEDGE CONSTRUCTION IN DIGITAL ENVIRONMENTS

In total $n = 30$ publications were included in our scoping review as shown in Table 1. We extracted journal papers ($n = 15$) and conference papers ($n = 15$) with publication years reaching from 1996 to 2020. The content of the publications was coded along the levels mentioned above of collaborative and individual knowledge construction [17, 35] to identify which design aspects promote different levels of knowledge construction. Detailed information about the publication years per venue type and the applied coding schema is available in the Supplementary Material of this publication.

Below, we summarise the reviewed literature that investigates individual (see Section 4.1), collaborative (see Section 4.2) or both knowledge construction types (see Section 4.3) through technology.

4.1 Individual Knowledge Construction

Individual knowledge construction is investigated in digital environments using different technologies. Derived from the literature reviewed, we structure the investigated technologies along with academic databases and online learning settings.

4.1.1 Individual Knowledge Construction in Academic Databases. Liu et al. [57] investigated individual knowledge construction during exploratory searches in academic databases. The results show that searching information, drawing and explaining concept maps supported levels of individual knowledge construction, such as simple processing (I), assimilation (II), deeper processing/reflection (III): *"By reading the related documents, participants discover concepts relating to the topic through [...] direct identification of potential keywords, extraction of concepts from underlying key sentences, creation of concepts [...]"* [57]. Knowledge restructuring (IV): *"With acquired concepts, participants begin to estimate relationships between these concepts"* [57], and meta-cognitive processing (V): *"concepts with high relevance are then clustered into knowledge communities"* [57], were reached. Thus the authors suggest implementing concept

Table 1. Publications in the Scoping Review with the Types of Knowledge Construction (KC) Covered and the Digital Environments Studied (I = Individual Knowledge Construction, C = Collaborative Knowledge Construction)

Publications	**KC Types**	**Digital Environments**
Liu et al. [57]	I	Academic Databases
Scutaru et al. [87]	I	Adaptive Learning Environment with Digital Tutor
Liaw et al. [54]	I	Mobile Learning Environment
D’mello and Graesser [16]	I	Learning Environment with Digital Tutor
Sun et al. [89]	I	Online Learning Environment
Harbarth et al. [36]	I	Video-Based Learning Environment
Yang et al. [98], Hew et al. [38, 39], Wang et al. [95], Aviv et al. [7]	C	Discussion Forum
Kanuka and Anderson [46]	C	Online Conference-Style Forum
Beers et al. [9], Heo et al. [37]	C	Online Learning Environment
Oeberst et al. [67]	C	Wikis
Rosen and Rimor [77]	I, C	Collaborative Database Learning Environments
Ertl et al. [25], Zahn et al. [99], Weinberger et al. [96], Hmelo-Silver [40], Oshima and Scardamalia [69]	I, C	Computer-Supported Collaborative Learning Environments
Suthers et al. [90], Kollar et al. [53]	I, C	Online Learning Environment
Ge et al. [33]	I, C	Open Source Software Development
Pérez-Sanagustín et al. [72]	I, C	Situated Learning Environment
Du and Wagner [19]	I, C	Weblogs
Kimmerle et al. [47–49], Moskaliuk et al. [65]	I, C	Wikis

map functionalities, automatic recommendation of associated concepts and assistance in determining links between different concepts to enhance individual knowledge construction [design heuristic 1.1].

4.1.2 Individual Knowledge Construction in Learning Environments with Digital Tutors. e,D’Mello and Graesser [16] studied the process of individual knowledge construction supported by an adaptive intelligent tutor. The tutor automatically recognises and responds to users’ cognitive states based on the users’ text and speech input. Sessions with the tutor include, e.g. encouragement, repeated questions about the users’ understanding, support in setting learning goals, and conversations about learning topics. This interaction enables the levels of simple processing (I), assimilation (II), deeper processing/reflection (III), knowledge restructuring (IV), and meta-cognitive processing (V). Thus, it can be recommended to encourage users, ask comprehension questions, conduct a dialogue on the learning subject and support setting learning goals to foster individual knowledge construction [design heuristics 1.2, 1.3].

Scutaru et al. [87] studied individualised learning experiences in an adaptive virtual reality (VR) learning environment with a digital tutor. The results suggest that feedback and general interaction with a tutor promoted the levels of simple processing (I), assimilation (II), deeper processing/reflection (III) of individual knowledge construction. Therefore providing feedback for learning activities and interacting with a digital tutor can be recommended to support individual knowledge construction [design heuristics 1.2].

4.1.3 Individual Knowledge Construction in Online Learning Environments. Harbath et al. [36] investigated individual knowledge construction in a video-based learning environment with functionalities such as concept maps, tagging, and flashcards.

Results show that learning videos promote the individual knowledge construction levels of simple processing (I) and assimilation (II). Tagging supports the level of deeper processing/reflection (III), as it helps *"[...] to identify the key concept of the videos"* [36]. Creating concept maps or flashcards supports the levels of deeper processing/reflection (III), knowledge restructuring (IV), and meta-cognitive processing (V) of individual knowledge construction, as it fosters *"[...] deeper understanding of a specific domain"* [36]. These actions support learners to *"[...] link the knowledge semantically [...]"* [36]. For facilitating individual knowledge construction with learning videos, the implementation of tagging, concept map, and flashcards functionalities can be suggested [design heuristics 1.1, 1.4, 1.6].

Liaw et al. [54] investigated different knowledge management functionalities in a mobile learning environment. For example, assisted decision making to select appropriate information sources (web pages) and the possibility to bookmark these web pages support the levels of simple processing (I), assimilation (II), and deeper processing/reflection (III). Additionally, in the environment, a categorisation functionality is provided to categorise web pages supporting the deeper processing/reflection level (III). Therefore, to support individual knowledge construction, supportive decision-making functionalities to select the right information source and bookmarking and categorisation functionalities for information sources could be integrated [design heuristics 1.5, 1.6].

Sun et al. [89] investigated individual knowledge construction in an online learning environment. The results show that the following integrated components support all five levels of individual knowledge construction: the definition of learning goals, the definition of skills relevant for respective tasks, and the visualisation of the expected learning outcomes in an ontology/concept map. Therefore, all three features should be provided to support individual knowledge construction [design heuristics 1.1, 1.3].

4.1.4 Summary of Design Heuristics. In order to enable and improve individual knowledge construction along with Dole and Sinatra [17], the following design heuristics (see Table 2) can be derived from the literature.

Table 2. Design Heuristics to Foster Individual Knowledge Construction

Design Heuristics & References	**Levels of Individual Knowledge Construction [17]**
1.1. Offer concept maps: offer recommendations for associated concepts, assistance for linking concepts, and visualisation of expected learning outcomes [36, 57, 89]	*Levels:* simple processing (I), assimilation (II), deeper processing (III), knowledge restructuring (IV), meta-cognitive processing (V)
1.2. Provide digital tutoring: encourage user, ask comprehension questions, conduct a dialogue on the learning subject, give feedback on learning activities, support the setting of learning goals [16, 87]	*Levels:* simple processing (I), assimilation (II), deeper processing (III), knowledge restructuring (IV), meta-cognitive processing (V)
1.3. Define learning goals and skills: define dedicated learning goals and required skills in respective task descriptions [16, 89]	*Levels:* simple processing (I), assimilation (II), deeper processing (III), knowledge restructuring (IV), meta-cognitive processing (V)
1.4. Provide functionalities to enhance learning videos: concept maps, tagging, quizzes and flashcards [36]	*Levels:* simple processing (I), deeper processing (III), knowledge restructuring (IV), meta-cognitive processing (V)
1.5. Offer supportive decision making: support the selection of suitable information sources [54]	*Levels:* simple processing (I), assimilation (II), deeper processing (III)
1.6. Organise information: offer bookmarking, tagging and categorisation features for information (sources) [36, 54]	*Levels:* simple processing (I), assimilation (II), deeper processing (III)

4.2 Collaborative Knowledge Construction

Collaborative knowledge construction is examined in digital environments using various technologies. Based on the literature reviewed, we structure the technologies studied along with discussion forums and social learning environments.

4.2.1 Collaborative Knowledge Construction in Discussion Forums. Yang et al. [98] investigated online cooperative translation activities in a discussion forum. Regarding collaborative knowledge construction, online discussion promoted the levels sharing/comparing of information (I), dissonance (II) and negotiation (III) - which indicates externalisation. Interestingly, *"the higher engagement students were more inclined to negotiate and co-construct knowledge repeatedly"* [98]. To support collaborative knowledge construction, they suggest integrating intelligent agents that offer timely guidance [design heuristic 2.2]. To raise motivation, *"moderate competitions between groups"* [98] is suggested [design heuristic 2.4].

Hew et al. [38, 39] focused on collaborative knowledge construction in online discussion forums. Results show that more externalisation and higher levels of collaborative knowledge construction (Level II - V) were promoted by i) bigger group size and ii) tutoring techniques, e.g. providing opinions or experiences as information, showing appreciation, encouraging contribution, summarising, and pointing out unresolved issues [39] [design heuristics 2.3, 2.9, 2.10].

An interactive learning environment and discussion forum were explored by Wang et al. [95]. Results show that only lower levels of collaborative knowledge construction were reached: mostly sharing/comparing of information (I), sometimes dissonance (II), and little negotiation (III). Therefore, mainly externalisation processes with little evidence of internalisation - were identified. The authors note that the discussion topic influences knowledge construction in discussions, so that the discussed topics need to be relevant and *"challenging and controversial enough to trigger different opinions"* [42, 95] [design heuristic 2.5]. Further, they recommend larger group sizes (minimum 3 to 5 collaborators) so that more diverse perspectives are expressed [design heuristic 2.10].

Aviv et al. [7] studied influence of differently structured learning networks in online environments with discussion forums. In the structured network, collaboration steps were predefined, while in the non-structured network, there was no organisational structure. Results show that in the structured network, all levels of collaborative knowledge construction were reached (I - V) - which indicates that information and ideas were externalised. In contrast, in the non-structured network, only level sharing/comparing of information (I) was reached [design heuristic 2.1].

Kanuka and Anderson [46] focused on a discussion forum implemented in an online conference-style environment. Most interactions there represented the level sharing/comparing of information (I) of collaborative knowledge construction. Thus externalisation of information took place. Only a few interactions reached all five levels, initiated especially by social discord. The authors derived two implications for supporting collaborative knowledge construction *"(a) the provision of learning opportunities that capitalise on inconsistencies and contradictions between participants, and (b) the incorporation of activities that help participants become explicit about their own understanding by comparing it with that of other participants"* [46] [design heuristics 2.1, 2.6].

4.2.2 Collaborative Knowledge Construction in Collaborative and Social Learning Environments. Oeberst et al. [67] investigated collaborative knowledge construction in the social system Wikipedia. They examined the collaboration of individuals who jointly wrote an article. Although most of the collaborators did not have domain-specific background education, experts rated the article as high quality. Thus, the highest level of collaborative knowledge construction, agreement (V), was achieved, and externalisation processes took place. The authors provide three explanations for this effect: First, different educational backgrounds were beneficial for collaborative knowledge construction. Second, the higher the number of collaborators, the better the quality of articles (also in [51] in [67]). Third, the effect could arise from Wikipedia and its rules itself, namely that information in an article is accepted or not [design heuristics 2.9, 2.10].

Regarding project-based learning in computer-supported collaborative learning (CSCL) environments, Heo et al. [37] found that groups with higher-rated projects exhibit levels of collaborative knowledge construction: sharing/comparing of information (I), dissonance (II), and negotiation (III) - thus externalised information, ideas, and viewpoints. To support reaching higher levels of collaborative knowledge construction and producing high-quality output, the authors proposed providing specific collaboration guidelines and visualising interaction patterns to reflect collaborators' participation. Regarding time management, project understanding, resource finding, and reflection guidance, they suggested implementing online tutors that offer adaptive support and feedback [design heuristics 2.1, 2.8].

Beers et al. [9] explored negotiation tools in online learning environments. The results show that negotiation tools with functionalities such as verification, agreement and disagreement of contributions facilitate collaborative knowledge construction. The levels sharing/comparing of information (I), negotiation (III), and agreement (V) were supported - thus supporting externalisation processes by providing a formalism for negotiation and coercing users to follow it. Therefore, to support collaborative knowledge construction, functionalities such as verification, agreement and disagreement of contributions and reminders of these actions can be recommended[design heuristic 2.7].

4.2.3 *Summary of Design Heuristics.*
To foster different levels of collaborative knowledge construction according to [35], design heuristics can be derived from the literature as presented below (see Table 3).

Table 3. Design Heuristics to Foster Collaborative Knowledge Construction

Design Heuristics & References	**Levels of Collaborative Knowledge Construction [35]**
2.1. Offer predefined guidance and steps, collaboration guidelines [7, 37, 46]	*Levels:* sharing/comparing of information (I), dissonance (II), and negotiation (III)
2.2. Provide timely guidance in discussions [98]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III)
2.3. Encourage participants to contribute, show appreciation, share information, offer adaptive support and feedback [38]	*Levels:* dissonance (II), negotiation (III), modification (IV), agreement (V)
2.4. Moderate competition between groups [98]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III)
2.5. Topics to be discussed need to be relevant, challenging and controversial [95]	*Level:* sharing/comparing of information (I)
2.6. Provide learning opportunities that focus on inconsistencies and contradictions [46]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III)
2.7. Allow verification, agreement and disagreement of contributions; send automatic reminders for these actions [9]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), modification (IV), agreement (V)
2.8 Visualise interaction patterns [37]	*Levels:* sharing/comparing of information (I), negotiation (III), agreement (V)
2.9. Ensure easy accessibility; encourage participation and collaboration by the tool itself [38, 67]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), modification (IV), agreement (V)
2.10. Groups sizes should not be too small to get more opinions and perspectives [38, 67, 95]	*Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), modification (IV), agreement (V)

4.3 Individual and Collaborative Knowledge Construction

Based on the literature reviewed, we present our results on individual and collaborative knowledge construction processes along with the technologies found by grouping them into computer-supported collaborative (learning) environments (CSCL), wikis and social tagging systems, and miscellaneous tools and environments.

4.3.1 *Individual and Collaborative Knowledge Construction in Collaborative and Social Learning Environments.*
Zahn et al. [99] examined information design and reflective discussion using digital video technology in CSCL environments. The authors examined discussions (discussion condition) and the integration of video excerpts into multimedia products (design condition). Results show that designing video-based content supports the levels of simple processing (I) and

assimilation (II) of individual knowledge construction and internalisation of new information. The design condition also led to the stronger integration of new information into collaborative work. Indicating that more information was externalised and the sharing/comparing of information (I) level of collaborative knowledge construction was achieved more frequently. Thus to promote individual and collaborative knowledge construction, video-based information design (e.g., designing a video-based website) can be suggested [design heuristic 3.3].

Ertl [25] investigated the influence of prior knowledge and supporting scripts on knowledge construction in computer-supported collaborative learning (CSCL) environments. Results w.r.t. individual knowledge construction indicate that prior knowledge about definitions and better collaboration promoted the levels of assimilation (II) and deeper processing/reflection (III). Collaborative knowledge construction up to the level of agreement (V) was enhanced by scripts offering content support and higher prior knowledge. To support the individual and collaborative knowledge construction, functionalities that enable, encourage and support the exchange of different perspectives are recommendable. Further, scripts for content support can be suggested [design heuristics 3.5, 3.6].

In a CSCL environment, Suthers et al. [90] compared collaborative graphical knowledge representations and discussions. One condition presented only text (text condition), one used graphical representations (graph condition), and the third offered both text and graphical (mixed condition); however, all presented the same information content. The results show that both graphical and mixed conditions promoted the level of deeper processing/reflection (III) of individual knowledge construction since (*"[...] more elaboration of hypotheses [...]"* [90] were made. The graphical condition supported more negotiation (III) and agreement (V) regarding collaborative knowledge construction. Integrating graphical knowledge representation tools can be recommended to support individual and collaborative knowledge construction [design heuristic 3.1].

Weinberger et al. [96] conducted three studies in CSCL environments. In the first study, Erkens et al. [24] investigated whether a chat tool in combination with a tool that visualises the contributions of group members supports knowledge construction in a group task. The results show that using this tool led to longer augmentations with different reasoning patterns. The participation tool supported externalisation and the levels sharing/comparing information (I), dissonance (II), and negotiation (III) of collaborative knowledge construction. Thus, tools that visualise contribution patterns can support collaborative knowledge construction [design heuristic 3.1]. Two studies by Weinberger et al. [97] examined the impact of interaction scripts in online discussions on argumentative processes. The results show that interaction scripts supported externalisation and internalisation of appropriate information. The script support fostered the collaborative knowledge construction levels sharing/comparing of information (I) and deeper processing/reflection (III) of individual knowledge construction. The authors suggest implementing supportive scripts that guide extensive elaboration of individual arguments, construction of concept-based and strongly task-based arguments to support individual and collaborative knowledge construction [design heuristic 3.4].

Kollar et al. [53] investigated collaborative argumentation processes supported by scripts in an online learning environment. Receiving scripts that offer collaboration guidance promoted the levels of deeper processing/reflection (III) and knowledge restructuring (IV) of individual knowledge construction. Scripts motivate to collaborate strongly and promote the levels of sharing/comparing of information (I) and modification (IV) of collaborative knowledge construction. To support individual and collaborative knowledge construction, scripts that provide step-by-step instructions for learning and working together could be implemented in online discussions [design heuristic 3.4].

Hmelo-Silver [40] conducted two studies in a computer-supported collaborative learning (CSCL) environment. In study 1, results regarding individual knowledge construction show that high prior knowledge leads to more statements indicating meta-cognitive processing (V). In terms of collaborative knowledge construction, the results show that high prior knowledge resulted in generating more questions and reaching sharing/comparing information (I), negotiation (III), and agreement (V) levels more often. In Study 2, the authors investigated a drawing tool integrated into a discussion forum. Results show that using the tool supported all levels (I-V) of collaborative knowledge construction. The author assumed that the drawing tool *"[...] served as a concrete referent that students can point towards and negotiate as they are elaborating and monitoring their joint understanding [...]"* [40]. Derived from both studies, offering task- or topic-related information before the discussion starts to establish prior knowledge and enhancing discussion forums with drawing tools to support individual and collaborative knowledge construction can be recommended [design heuristic 3.2].

In a computer-based learning environment, Oshima and Scardamalia [69] explored theory learning and recording of related thoughts in the form of text or graphic notes in a database. Note analyses revealed that high conceptual change is associated with more appropriate mental models. Thus, the levels of assimilation (II), knowledge restructuring (IV) and meta-cognitive processing (V) are reached, and new concepts are internalised. In terms of collaborative knowledge construction, conceptual change more often led to the level of sharing/comparing information (I), i.e. own knowledge was integrated, and collaborative knowledge construction was used for goal setting to tackle new problems and support others. For fostering individual and collaborative knowledge construction, tools should enable frequent reflection of current understanding and provide functionalities for integrating own knowledge and collaborative learning goals [design heuristic 3.7].

4.3.2 Individual and Collaborative Knowledge Construction in Miscellaneous Environments. Pérez-Sanagustín et al. [72] studied the use of two types of quick response (QR) codes - bidirectional and traditional QR codes, in situated learning environments. Both QR code versions present (when scanned) information, bidirectional QR codes additionally present information-related closed and open questions that can be answered collaboratively and allow users to annotate information. Individual knowledge construction level deeper processing/reflection (III) was supported by information-related open questions, indicating internalisation of new information. In addition, the tagging functionality and information-related open questions supported externalisation and communication, as well as collaborative knowledge construction levels such as sharing/comparing information (I), negotiation (III), and agreement (V). To support individual and collaborative knowledge construction, the authors have suggested functionalities that enable collaborative question answering - especially open questions [design heuristic 3.9]. For collaborative knowledge construction, the integration of tagging functionality is recommended [design heuristic 3.10].

Rosen and Rimor [77] investigated the creation of written statements about different types of knowledge, collaborative discussion and classification of the statement (e.g. confirmation or agreement) in a collaborative database learning environment. Results show that the correct classification of statements in the forum initiated individual knowledge construction. Regarding collaborative knowledge construction, results show that more active discussants were more likely to reach all levels (I-V) as they discussed, argued and contributed to group agreement more. In contrast, less active discussion participation was more likely to lead to the level of deeper processing/reflection (III) of individual knowledge construction and internalisation of information. The authors suggest concerning design and action orientation that *"[...] there is a need for the characterisation of learners according to their tendency for group and individual work and to balance the groups in accordance with these features."* [77] [design heuristic 3.4].

Du and Wagner [19] investigated the functionalities of weblogs and their potential for individual and collaborative knowledge construction. Their analysis focused on weekly blogposts about learning activities and reading, evaluating and commenting on one's own and other blogposts. The results show that accurate and conscientious blog posting supported the construction of advanced mental models, internalisation and thus high levels of individual knowledge construction (levels III-V). In addition, this was associated with more substantial collaborative knowledge construction at the level of sharing/comparing of information (I) and thus with stronger externalisation. The authors suggest using weblogs including functionalities for reading, reviewing, commenting and prompting to enhance learning performance, individual and collaborative knowledge construction [design heuristic 3.8].

Ge et al. [33] analysed collaboration tools in an open-source software development community. These tools, e.g. chats and software development coordination tools, promote levels of individual knowledge construction, such as assimilation (II) and deeper processing/reflection (III). Discussions about problem design, representation and solution promote deeper processing/reflection (III), knowledge restructuring (IV), and meta-cognitive processing (V). Sharing/comparing of information (I) happened during communication in collaboration tools. Discussions about problem definition and presentation support the levels of sharing/comparing of information (I), negotiation (III), and agreement (V) of collaborative knowledge construction. Using a monitoring functionality that allows users to see the progress and solution of core developers enhances negotiation (III) and knowledge restructuring (IV).

4.3.3 Individual and Collaborative Knowledge Construction in Wikis and Social Tagging Systems. Moskaliuk et al. [65] and Kimmerle et al. [47–49] investigated individual and collaborative knowledge construction processes in wikis. In the study by Moskaliuk et al. [65] participants created wiki entries based on a given set of arguments. Either ten arguments (full condition), four arguments (one-sided condition) and no arguments (no-content condition) were available to formulate the wiki entry. Still, all arguments could be read in advance. The one-sided condition led to a deeper understanding of the topic at the individual level. Thus, individual cognitive accommodation processes took place, and the level of deeper processing/reflection (III) was reached. At the collaborative level, restructuring of the text and an explication of different positions indicated collaborative accommodation processes took place and the levels of sharing/comparing of information (I), negotiation (III) and modification (IV). In addition, more new facts were added to prior knowledge in the one-sided condition. Hence, the assimilation (II) level of individual knowledge construction is reached. The results of similarly structured studies by Kimmerle et al. [47–49] support these findings. Therefore, to support individual and collaborative knowledge construction in wikis, it is recommended to present only a subset of arguments that can be adapted and extended [design heuristic 3.5], rather than all arguments.

Kimmerle et al. [49] investigated the influence of social tagging activities on individual and collaborative knowledge construction. Tagging describes the (collaborative) assignment of keywords to digital resources (e.g. publications, photos, videos). A large number of assigned keywords can be considered a tag cloud. The authors investigated how tag clouds and various tagging activities (e.g. adding tags, searching for resources to tag) are used to construct knowledge. The results showed that by searching and studying information that is already tagged or could be tagged, information is internalised, and assimilation (II), deeper processing/reflection (III) and knowledge restructuring (IV) levels of individual knowledge construction are achieved. Furthermore, newly discovered resources are often tagged and thus support levels of sharing/comparing of information (I) and modification (IV) of collaborative knowledge construction. To support individual knowledge construction, tag clouds, the study of tagged information, and the search for new information that could be tagged can be recommended. For supporting collaborative knowledge construction, tagging of newly discovered resources can be recommended [design heuristic 3.10].

4.3.4 Summary of Design Heuristics. The following design heuristics (see Table 4) that facilitate the levels of individual and collaborative knowledge construction according to Dole and Sinatra [17] and Gunawardena et al. [35] can be derived from the literature.

Table 4. Design Heuristics to Foster Individual and Collaborative Knowledge Construction

Design Heuristics & References	**Levels Individual [17] and Collaborative [35] Knowledge Construction**
3.1. Graphical tools: visualize knowledge with e.g. graphs; visualize individual contributions to group collaboration [24, 90]	*Indiv. Level:* deeper processing/reflection (III) *Collab. Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), agreement (V)
3.2. Monitoring/collab. tools: present progress and solutions of others; enable collaboration e.g. via a drawing tool [33, 41]	*Indiv. Level:* meta-cognitive processing (V) *Collab. Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), modification (IV), agreement (V)
3.3. Video-based tools: support online discussions; support the design of information content [99]	*Indiv. Levels:* simple processing (I), assimilation (II) *Collab. Level:* sharing/comparing of information (I)
3.4. Guide argumentation processes [53, 77, 96]	*Indiv. Levels:* deeper processing/reflection (III), knowledge restructuring (IV) *Collab. Levels:* sharing/comparing of information (I), modification (IV)
3.5. Recommend concepts, arguments, definitions or theoretical knowledge [25, 47–49, 65]	*Indiv. Levels:* assimilation (II), deeper processing/reflection (III) *Collab. Levels:* sharing/comparing of information (I), dissonance (II), negotiation (III), modification (IV), agreement (V)
3.6. Encourage and support the exchange of different perspectives [25]	*Indiv. Levels:* assimilation (II), deeper processing/reflection (III)
3.7. Foster reflection, collaboration, and goal setting [69]	*Indiv. Levels:* assimilation (II), deeper processing/reflection (III), knowledge restructuring (IV), meta-cognitive processing (V) *Collab. Level:* sharing/comparing of information (I)
3.8. Weblogs: offer reviewing, commenting and prompting functionalities [19]	*Indiv. Levels:* deeper processing/reflection (III), knowledge restructuring (IV), meta-cognitive processing (V) *Collab. Level:* sharing/comparing of information (I)
3.9. Questions: Offer collaborative (open) questions [72]	*Indiv. Levels:* deeper processing/reflection (III) *Collab. Levels:* sharing/comparing of information (I), negotiation (III), and agreement (V)
3.10. Tagging: offer collaborative tagging and tag clouds [49, 72]	*Indiv. Levels:* assimilation (II), deeper processing/reflection (III), and knowledge restructuring (IV) *Collab. Levels:* sharing/comparing of information (I), negotiation (III), and agreement (V)

5 DISCUSSION: DESIGN IMPLICATIONS FOR OPEN SCIENCE

This section lays out how we have developed the design heuristics into a design space for supporting knowledge construction in open science.

5.1 Designing for Knowledge Construction: Design Categories

When reflecting on the identified design heuristics, we see that they speak about technical functionalities that support knowledge construction and that these functionalities, in turn, can be grouped. Subsequently, we developed three design categories into which these functionalities fall: i) Design Category 1 (DC1): functionalities for structuring and supporting collaboration, ii) Design Category 2 (DC2): functionalities for supporting the learning process, and iii) Design Category 3 (DC3): functionalities for structuring, visualising and navigating (learning) content. DC1 subsumes interactions, such as guiding, supporting and visualising collaboration and communication. DC2 is dedicated to functionalities for enriching the learning process with additional information and materials. DC3 contains functionalities for visualising information and thus making this content more understandable and accessible. Figure 3 shows how the design heuristics are associated with these three design categories and the overlaps between the three design categories.

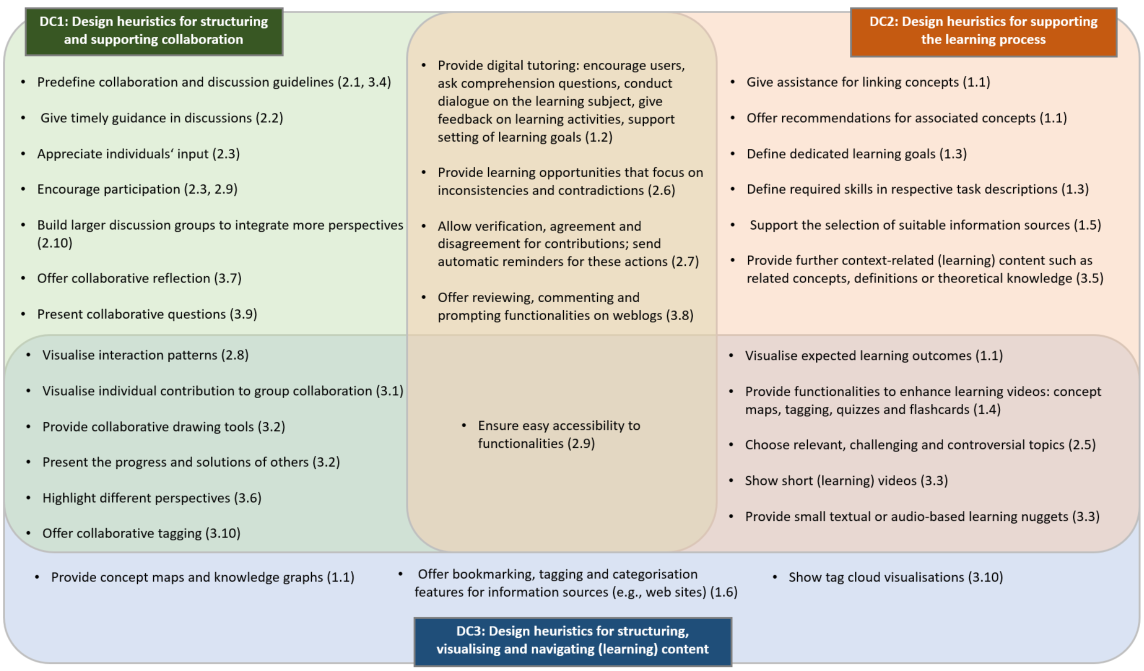

Fig. 3. Mapping the Design Heuristics (with Numeration) to the Design Categories and their Overlaps.

The three design categories point to scientific communities that conduct research on functionalities and technologies in these categories. Computer-supported cooperative work (CSCW) as well as computer-supported collaborative learning (CSCL) communities, e.g. [43, 56, 58, 59, 68, 78, 91], investigate functionalities and technologies in DC1: Structuring and supporting collaboration. HCI-oriented research communities around learning and technologies, e.g. [2, 13, 31, 44, 62, 63], investigate functionalities and technologies in DC2: Supporting the learning process. The information retrieval and recommender system communities investigate functionalities and technologies, e.g. [12, 18, 52, 100], that fall into DC3: Structuring, visualising and navigating of (learning) content.

Our design categories are also in line with the model we used for our literature review (see Fig. 2). The most obvious alignment is that DC1 supports collaborative knowledge construction processes, and DC2 supports individual knowledge construction, i.e. learning. Thus, DC1 and DC2 are categories that support knowledge construction processes through functionalities that motivate active participation. The third design category, DC3, about structuring, visualising and navigating the (learning) content did not emerge accidentally. Instead, DC3 orients towards knowledge that has already been made explicit in artefacts that reside outside the individual and social systems described by the knowledge construction model. DC3 are functionalities that make such external resources available and more accessible to individual and social systems.

Despite these alignments, we note that the knowledge construction model is ontologically different from the three design categories. The knowledge construction model describes two processes for knowledge construction - collaborative/social and individual/cognitive - while the design categories are categories of technical functionalities. The design categories serve as a bridge between psychological and design-oriented bodies of knowledge.

5.2 Design Implications for Knowledge Construction in Open Science

In this section, the final step towards laying out the design space for supporting knowledge construction in open science is taken by systematising how existing design knowledge could be used in open science platforms to facilitate knowledge construction and thereby support the uptake of open science resources.

As there are already existing, successful open science platforms, the question arises: To which of their components could functionalities for supporting knowledge construction be attached? To address this question, we selected ten popular platforms based upon the competitor analysis of Dumouchel et al. [20] and used the Alexa ranking [3] to verify the popularity of the platforms. Table 5 lists platform names, the type of the platforms, and core components. Most platforms have components for searching and reading scientific literature. Other components integrated on more than one platform we analysed are (number of platforms in brackets): social networking (5); discussion forums (4); author profiles (4); content curation (3); usage and/or impact metrics (3); track recent developments of research areas (2).

Of these, we discuss the following components as anchors for designing for knowledge construction: 1) search (and read) scientific literature, authors, citations, etc.; 2) social networking; 3) discussion forums; 4) content curation; and 5) usage and impact metrics.

In an iterative process of collaborative reflection in the authoring team, we mapped the design categories and the associated design heuristics to the core components of open science platforms as summarised in Figure 4.

Finally, we have developed this mapping into design implications (DI) in the sense of proposals for supporting knowledge construction in open science platforms. The design implications (DI1 - DI18) are based on knowledge construction theory, evidence about designing for knowledge construction in other contexts (design heuristics), and knowledge about typical open science platforms.

Easy accessibility (DI1): The design heuristic that belongs to the overlap of all three design categories leads to easy accessibility as a generally applicable requirement for all open science platforms [design heuristic 2.9 [38, 67]].

Discussion guidance (DI2) and collaborative reflection (DI3): The design heuristics assigned to DC1 are mostly related to discussion forums. This complies perfectly with the core components of existing open science platforms as many of them have already discussion forums implemented [2]. Consequently, we see as design implications to design discussion guidance (DI2) and support collaborative reflection (DI3). By discussion guidance we mean, to offer dedicated discussion guidelines and interventions to encourage platform users to participate, highlighting other viewpoints, or showing appreciation for input or by providing feedback.

Table 5. Ten Most Popular Open Science Platform based upon Dumouchel et al. [20] and Alexa Ranking [3]

Platform Name	Type of Platform	Core Components
Google Scholar (https://scholar.google.at)	academic search engine	Search (and read) scientific literature, related works, authors, citations; track recent developments of research areas; author profiles; usage metrices [85]
GitHub (https://github.com)	open source software development community	Collaborative coding; open source code; social networking; discussion forums [34]
ResearchGate (https://www.researchgate.net)	science-oriented social media	Search (and read) scientific literature, related works, authors, citations; social networking; author profiles; publication and project sharing; discussion forum; research focused job board [76]
Academia.edu (https://www.academia.edu)	science-oriented social media	Search (and read) scientific literature, related works, authors, citations; content curation (summary of papers); track recent developments of research areas; author profiles [1]
Elsevier (Open Science) (https://www.elsevier.com)	academic search engine	Search (and read) scientific literature, related works, authors, citations; social networking; discussion forums; usage and impact metrices; content curation (audio slides, information aggregation) [23]
JSTOR (https://www.jstor.org)	search engine and directory for OA resources	Search (and read) scientific literature, related works, authors, citations; text and data mining for users; usage metrices [45]
arXiv.org (https://arxiv.org)	search engine and directory for OA resources	Search (and read) scientific literature, related works, authors, citations; usage metrices [5]
Semantic Scholar (https://www.semanticscholar.org)	academic search engine	Search (and read) scientific literature, related works, authors, citations; usage and impact metrices [86]
Frontiers (https://www.frontiersin.org)	academic search engine	Search (and read) scientific literature, related works, authors, citations; social networking; authors profiles; usage and impact metrices [30]
Mendeley (https://www.mendeley.com)	science-oriented social media	Reference managing and search; social networking; discussion forum; author profiles; usage and impact metrices; content curation (content suggestions) [61]

This could enhance the outcome of scientific discussions and enable knowledge construction [design heuristics 2.1, 2.3, 3.4, 3.6 [7, 25, 37–39, 46, 53]].

By supporting collaborative reflection, we mean that reflection prompts can be given to users after they have read an open science resource or have read or contributed to a discussion forum. Such prompts can promote reflection [design heuristics 3.7, 3.9 [25, 72]] and have been proven to be beneficial for the uptake and understanding of complex scientific content [8, 25, 72].

Digital tutoring (DI4), interactive functionalities (DI5), and learning opportunities (DI6): The design heuristics situated in the overlap of DC1 and DC2 focus on social, reflective and informative interactions. They can be mapped to discussion forums and social networking functionalities and inform open science platforms' content curation. Consequently, we see as design implications to integrate digital tutoring (DI4), design for social interaction (DI5), and learning opportunities (DI5). By digital tutoring functionalities, we mean to encourage users, ask comprehension questions, conduct dialogue on learning subjects, give feedback on learning activities, or support the setting of learning goals [design heuristic 1.2 [16, 87]]. These are all actions that support knowledge construction.

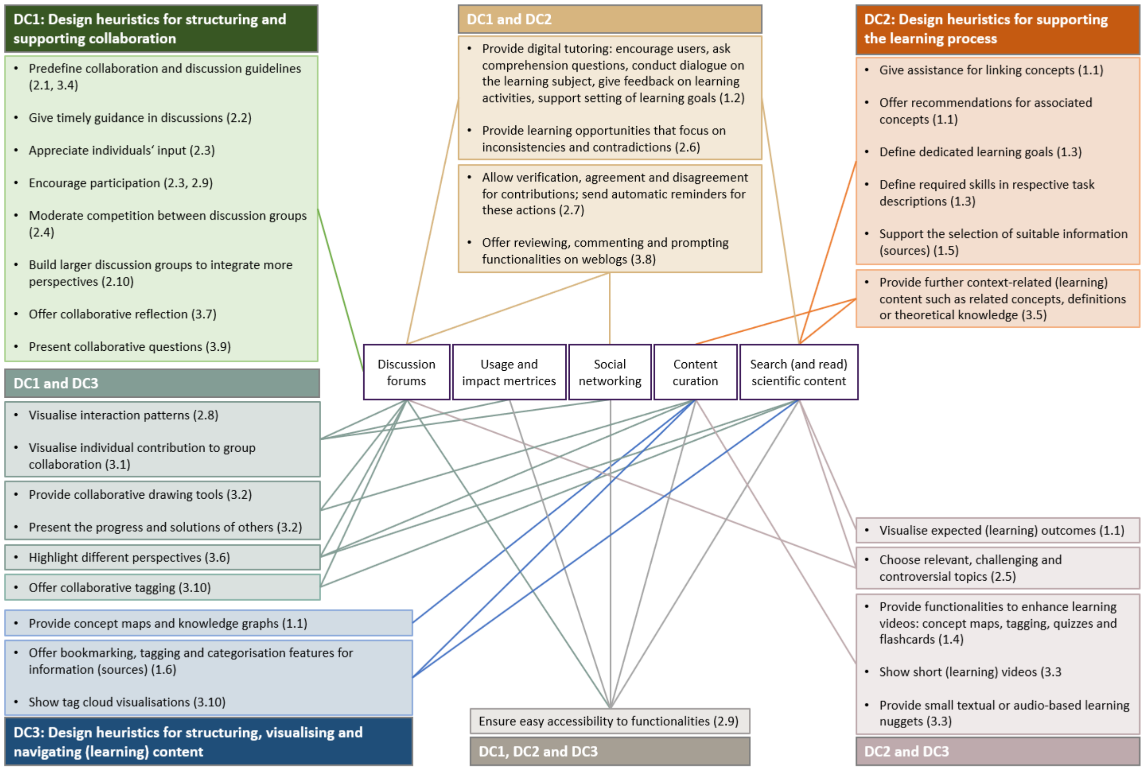

Fig. 4. Mapping Design Heuristics to Core Components of Open Science Platforms.

By interactive functionalities, we mean to design for social interactions by adding functionalities for reviewing, commenting, prompting and allowing verification, agreement and disagreement for contributions [design heuristics 2.7, 3.8 [9, 19]]. This could promote participation, reflection and giving peers feedback [9, 19].

By designing learning opportunities, we mean to provide learning opportunities that make users aware of inconsistencies and contradictions [design heuristic 2.6 [46]]. This could trigger the evaluation of different aspects of topics [10] and improve the quality of discussion.

Learning process guidance (DI7), understanding of content (DI8) and additional learning content (DI9): The design heuristics derived from literature for DC2 primarily refer to providing additional (processed) learning material. They can be mapped to the core components search (and read) scientific content and content curation. Consequently, we see as design implications to develop guidance for the learning process (DI7), support the understanding of content (DI8), and recommend additional content (DI9) to users. By guiding the learning process, we mean that supporting the selection of suitable information (sources), defining dedicated learning goals and required skills for specific tasks (e.g. search tasks) [design heuristics 1.5, 1.3 [16, 54, 89]] could support the literature search and reading process.

By supporting the understanding of concepts, we mean to offer assistance for linking concepts and recommendations for associated concepts [design heuristic 1.1 [57, 90]]. This could enhance the literature search process and lead to a deeper understanding of scientific contexts. By offering additional learning content, we mean that intelligent interventions could recommend further context-related (learning) content to explore related concepts, and definitions or theoretical knowledge to make complex scientific content more understandable [design heuristic 3.5 [25]]. These actions favour the understanding of complex scientific content [14], and on-the-fly delivery could promote the uptake of this content.

Processed learning content (DI10) and topic recommendation (DI11): The design heuristics that belong to the overlap of DC2 and DC3 refer mainly to processing, selecting and/or recommending suitable learning content. They can be applied to content curation and search (and read) scientific content and partly to discussion forums. Consequently, we see as design implications to offer content pre-processed for learning and knowledge construction (DI10) and to recommend topics for reading and discussion (DI9). By offering processed learning content, we mean to offer scientific information in different ways such as textual or audio-based learning nuggets, or short (learning) videos [design heuristic 3.3 [99]] to foster better understanding of complex content.

By recommending topics, we mean that relevant, challenging and controversial topics could be recommended for (reading and) discussion [design heuristic 2.5 [95]]. This can lead to more reflection on arguments and ideas in discussion forums [10].

Knowledge visualisation (DI12), knowledge organisation (DI13) and tag clouds (DI14): The design heuristics for DC3 relate to the preparation and the visualisation of information. These can be applied to the core components of content curating and searching (and reading) scientific content of existing open science platforms. Consequently, we see as design implications to visualise knowledge (DI12), organise knowledge (DI13) and specifically to use tag clouds (DI14). By knowledge visualisations, we mean to visualise complex concepts with the help of concept maps and knowledge graphs [design heuristic 1.1 [22, 57, 90]]. This can be useful to learn and understand more easily the relationships of complex scientific learning content and resources [60]. By supporting knowledge organisation, we mean to support bookmarking, tagging, and categorisation features for information [design heuristic 1.6 [36, 54]]. These features are helpful for structuring the search and the overall knowledge construction process.

Tag clouds visualise the most important keywords or concepts regarding a topic in a cloud [design heuristic 3.10 [49, 72]] By aggregating content, tag clouds can lead to a deeper understanding of scientific interrelationships [49, 72], which could be helpful in the search process.

Collaboration visualisation (DI15), collaborative tagging (DI16), collaborative drawing (DI17) and highlighting viewpoints (DI18): The design heuristics that belong to DC1 and DC3 focus on interactive visualisation tools that are applicable to discussion forums, content curation and search (and read) scientific content components. Consequently, we see as design implications to visualise the collaboration (DI15), to support collaborative tagging (DI16) and drawing (DI17), and to highlight (different) viewpoints (DI18). By collaboration visualisation we mean to visualise individual contributions in group collaborations and to show interaction patterns [design heuristics 2.8, 3.1 [24, 37, 90]]. This allows platform users to see ongoing developments and facilitates active participation, which is beneficial for individuals and open science communities [6] and thus complements social networking features and usage and impact metrics.

We suggest integrating collaborative tagging because organising and sharing scientific information resources through collaborative tagging [design heuristic 3.10 [49, 72]] allows users to directly find appropriate, related information [32].

We further suggest to integrate collaborative drawing [design heuristic 3.2 [33, 40]], as collaborative drawing can support collaboration in teams and the explanation of complex interactions [33, 40].

Finally, we suggest to highlight (different) perspectives and viewpoints, and to present progress, thoughts and solutions of others [design heuristics 3.2, 3.6 [25, 33, 40]]. This offers the possibility to learn from others to improve own questions and tasks [64].

Finally, in Figure 5, we have organised the design implications into columns according to the core components to which they could be attached. The design implications are sorted into boxes within each column representing the design categories and intersections. Note that in Figure 5 we have added specific examples of how to operationalise the design implications in concrete terms. We have added these examples firstly to make the design implications more tangible. Secondly, we hope they will serve as inspiration for research and design. The examples are not currently underpinned with empirical evidence regarding knowledge construction in open science environments but are based on grounded empirical (through the papers in the scoping review) and conceptual work (knowledge construction theory and our synthesis).

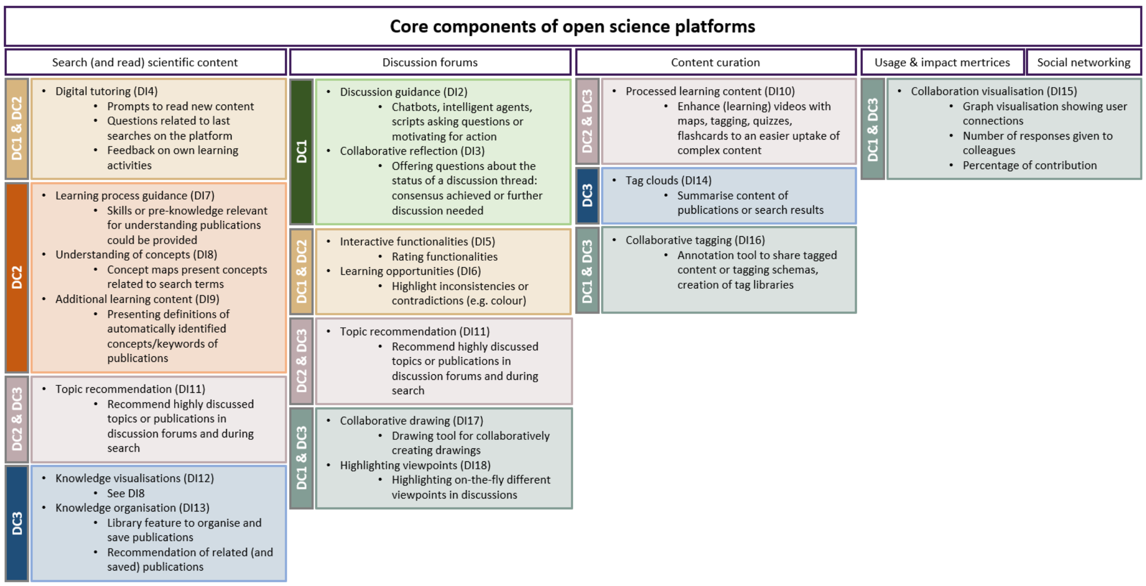

Fig. 5. Example Ideas for Operationalising the Design Implications.
The figure should be read as follows: The columns represent core components of existing open science platforms. The associated design categories (and their intersections) are shown in each column as coloured boxes. Each design category or intersection contains the associated design implications as the first text level. For example, the upper left box is in the column of the core component "Searching (and reading) scientific content". For this component, the design implication "Digital Tutoring (DI4)" is recommended, as it derives from the overlap of design categories 1 and 2 and can be integrated into functionalities for searching and reading scientific content. The bullet points below represent more concrete example ideas for the implementation of this design implication, e.g., prompting users to read new content, prompting users to ask questions about their recent searches or readings on the platform, or providing feedback to users about their learning activities on the open science platform.

6 CONCLUSION

In summary, we see that HCI research does not systematically research how to support open science through design. We address this gap in the present work starting from a learning perspective, i.e. the view that knowledge construction must happen to take up open science knowledge. Further, we take a design-oriented perspective by arguing that knowledge construction can be designed for. We have systematically collected existing knowledge on how to design for knowledge construction in a scoping review. In this, we found a single paper that discusses designing for knowledge construction in open science. However, existing designs for knowledge construction that work in other contexts such as in learning environments can inform the technology design of open science platforms. One strong message of our paper is, therefore, that there is ample space to contribute both to HCI and to open science by studying how to support knowledge construction in open science. From existing literature in other domains than open science, we derived design heuristics, which are empirically substantiated guidelines on how to support knowledge construction. In a subsequent synthesis, we grouped the underlying technological functionalities into three design categories: Structuring and supporting collaboration (DC1), supporting the learning process (DC2), and by structuring, visualising and navigating (learning) content (DC3). These categories can be related to models of knowledge construction and ongoing research in design- and HCI-oriented research communities. Finally, we mapped the three design categories and associated design heuristics to core components of open science platforms, and thereby developed design implications for supporting knowledge construction in open science. This mapping constitutes a partial design space for supporting knowledge construction in open science platforms. As the proposed design implications have not been investigated in relation to open science, they also provide a direction of necessary and exciting further research and innovation activities. We hope that researchers and designers will find it helpful as a map of where to start.

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