A systematic review of empirical studies on multidisciplinary design collaboration: Findings, methods, and challenges

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While multidisciplinary collaboration is increasingly considered as a prerequisite for innovation in design, it is unclear what has been studied and what to investigate next. To address this, we conducted a systematic literature review on multidisciplinary design collaboration, focussing on what has been found, and how these studies have been implemented. Following a PRISMA approach, 17 papers were selected for a critical review. A co-occurrence analysis found that the selected literature covered five themes centred on communication, all highlighting the importance of shared understanding in multidisciplinary design collaboration. Further analysis revealed biases and differences between the methodological approach followed in the studies. For future research, we suggest investigating two under-explored areas of design collaboration: distributed work and digital/service-oriented design activities.

Keywords: collaborative design, communication, design activity, interdisciplinarity, teamwork

Collaboration lies at the heart of design activity, and in the past thirty years, a significant body of research has focused on the empirical study of team collaboration during designing activities, for example the Design Thinking Research Symposium (DTRS) series that launched in 1991. Over the years, research into multidisciplinary design collaboration has rendered a complex discourse with differing findings. While an extensive body of literature highlights the benefits of multidisciplinary collaboration (De Luca & Atuahene-Gima, 2007; Milliken & Martins, 1996; Troy et al., 2008), the latter is also found to be associated with challenges related to integrating diverse knowledge (Cronin & Weingart, 2007; Lovelace et al., 2001; Van Der Vegt & Bunderson, 2005). As a result, it is unclear to conclude what has already been investigated and explored, as well as how, and what to study next.

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However, there has not yet been a systematic review of the findings and methodological analysis of how these studies on multidisciplinary design collaboration were conducted. Our systematic review on the relevant studies bears

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threefold objectives: (1) to synthesise and identify patterns in the literature, (2) acknowledge the diversity of results through a methodological analysis, and (3) clarify current challenges and provide recommendations for future research (Figure 1). This paper aims at answering the following research questions: (1) *What is our current understanding of multidisciplinary collaboration in relation to design teamwork*, and (2) *How previous studies have been conducted through their experimental choices, and adopted setups?*

The paper is structured as follows: We first present the scope of the paper, i.e. multidisciplinary design collaboration (Section 1). We then describe our methodological approach (Section 2) which consists of a systematic review of the literature (PRISMA), supported by a co-occurrence analysis of the findings of the papers and a meta-analysis of the designs and variables of the studies. We then present the results of our literature review: Section 3 presents ***what has been studied***, i.e. the findings of previous studies organised in thematic clusters, and Section 4 reports ***how it has been studied***, i.e. a methodological analysis reporting the designs of the studies, and their variables. Finally, we provide a synthesis of the results, as well as recommendations for future research.

The originality of this paper lies in the combination of a common approach for systematic literature review, i.e. PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) (Moher et al., 2009; Page et al., 2021) with a novel approach to semantic analysis and knowledge mapping, i.e. co-word analysis with co-occurrence network, based on text mining and natural language processing – NLP (Callon et al., 1983; Van Eck & Waltman, 2014).

1 Scope of the paper: multidisciplinary design collaboration

The main focus of this paper is the study of *multidisciplinary design collaboration*, specifically the scientific examination of the teamwork mechanisms and behaviours, in functionally diverse teams, that aim to produce creative outputs. Agogué et al. (2014) suggest that disciplinary backgrounds might also affect the scope of solution analysis: e.g. industrial designers might be more capable of overcoming design fixation than engineers, where engineers tend to create less variety of solutions compared to designers. On the other hand, Gero et al. (2019) noted that engineering design education plays a significant role in the development of design creativity. In fact, engineering firms now integrate various types of knowledge in their projects (Sonnenwald, 1996), where such a skill–set combination created for a particular purpose is defined in the industry as cross-functional teamwork (Parker, 2003).

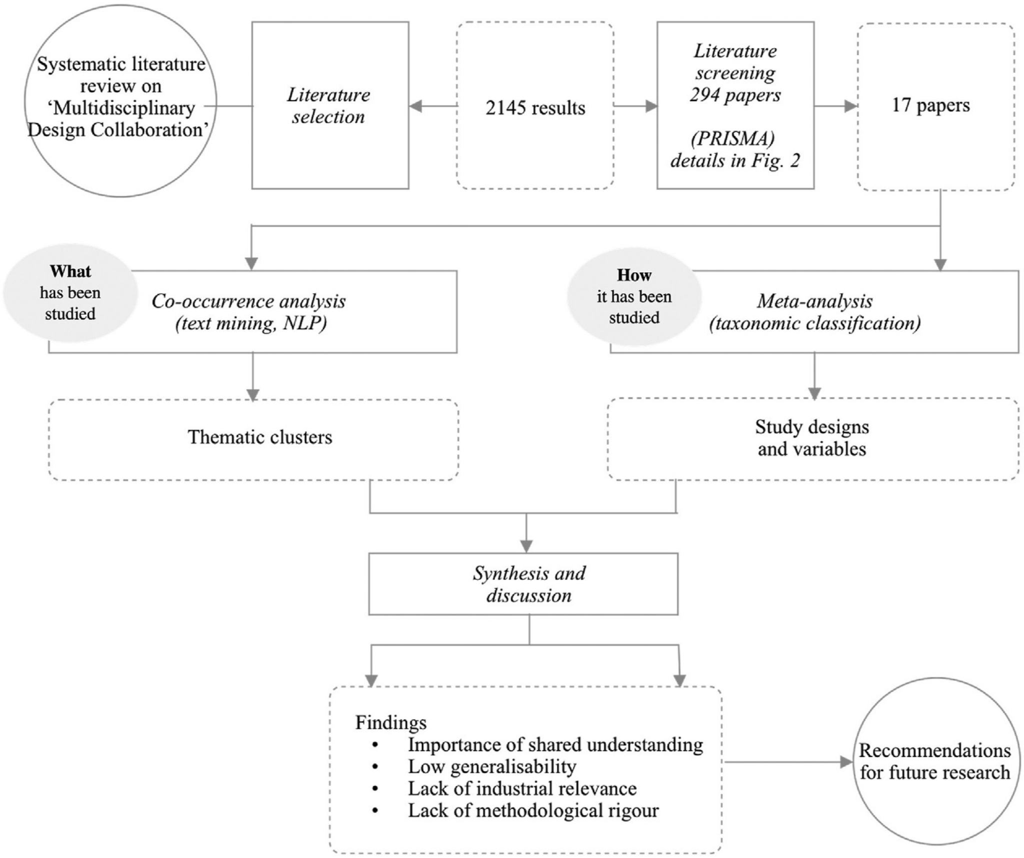

Figure 1 Overview of the study

Three different terms are used in the literature to describe cross-disciplinary practice where transgression into and across other disciplines takes place (Adams et al., 2009): *multidisciplinary* - joining together of disciplines to work on common problems and split apart when work is done, *interdisciplinary* - joining together of disciplines to work or identify common problems, and interaction may form new knowledge, and *transdisciplinary* - beyond interdisciplinary combinations to a new understanding of relationships between science and society. Few studies refer to *interdisciplinary* as a separate level or practice in the disciplinary integration differentiation (see Miller & Miller, 1982; Porter et al., 2006; Stember, 1991). Van den Besselaar et al. (2001) define a higher level of synthesis with the term "transdisciplinary", where the process of convergence between disciplines occurs with mutual integration of disciplinary epistemologies. While a set of scholars who focus on cross-disciplinary work have attempted to draw theoretical or philosophical distinctions among terms (Choi & Pak, 2006), in practice many researchers studying such collaboration use the terms interchangeably (see Kasali &

Nersessian, 2015). In other words, Klein (2008) is attempting to theorise different modes of collaborating across disciplinary boundaries, but the people interested in how the collaborations work are often less concerned with the terminology and more concerned with the collaboration itself. In fact, while solving complex problems, all team participants do cross their knowledge boundaries and synthesise practices from each other's disciplines (Kleinsmann et al., 2012). So, for ease and consistency throughout the paper, we refer to all layers of collaboration by the term *multidisciplinary*. Given the importance of communication as a core concern in cross-disciplinary collaborations, significant work in this area exists in a variety of domains, including the body of literature on communication. For this review, we limit the scope of the work to design studies in order to survey design researchers' existing understanding of such collaboration.

2 Methodology

This review of literature consisted of (1) a comparative theoretical synthesis of patterns and themes, supported by co-occurrence analysis, and followed by (2) a methods-oriented perspective inquiry of a meta-analysis (Robson & McCartan, 2016). The systematic review protocol ensures a rigour in screening and selection of the literature, as inclusion and exclusion criteria are applied in a systematic way. This approach is argued to provide completeness and depth of the analysis (Hay et al., 2017). The following critical review covers the themes unearthed by the co-occurrence analysis, whereas the meta-analysis acknowledges and surveys the diversity in the findings based on methodological factors, as in (Vasconcelos & Crilly, 2016), and raises questions for further research.

2.1 Literature screening and selection

2.1.1 Search protocol

The selection of the literature followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol — a widely used method for systematic review of scientific publications (Moher et al., 2009; Page et al., 2021). In order to mitigate biases related to selective reporting of outcomes, the protocol involves the selection of all publications on a given topic that meet pre-specified inclusion criteria (Shamseer et al., 2015). Although there are examples of systematic reviews in other areas of design studies, i.e. design cognition (Hay et al., 2017; Jin & Benami, 2010), this paper is the first systematic review of the literature on multidisciplinary design collaboration (Figure 2). The following databases were searched for articles published in peer-reviewed journals: Science Direct, Thomson Reuters Web of Knowledge, MIT Press Direct, and Taylor & Francis Online. From a pool of 2145 publications on *multidisciplinary collaboration*, only 294 articles reported studies within a *design context*. To ensure that the selected papers met high quality standards, we screened the top four *general design* research journals suggested by Gemser et al. (2012, p. 12) and Cash (2018): Design Studies, Design Issues, Journal of Engineering Design (JED), and International Journal of Design (IJD), and included CoDesign (since DTRS7 and DTRS10 were published in its Special Issues) in our search within the bibliometric databases using the structure of the search terms in Table 1. We additionally included other relevant publications by searching citations from included articles to broaden the candidate articles dataset, from journals, conferences, and books (see B. Christensen et al., 2017) following a references check.

2.1.2 Selection protocol

Figure 2 presents the selection protocol following PRISMA methodology (Moher et al., 2009).

2.1.3 Inclusion and exclusion criteria

The evaluation of articles against the six established inclusion criteria (see Table 2) resulted in the selection of the 17 publications published between 1992 and 2021 (see Appendix 2).

Excluded papers (see Appendix 1) are publications that did not fulfil the disciplinary diversity criterion – against the inclusion criteria no. 6 (see Table 2). For example in (Badke-Schaub et al., 2010, p. 123) where the examined team, defined as *multidisciplinary*, was in fact "composed as diversely as possible (male and female *designers*, of different nationalities with a different amount of expertise)". Or studies that do not sufficiently demonstrate the multidisciplinarity of the team, as in (Gruenther et al., 2009, p. 725) where the team is "composed of *engineering students* from several majors". Or studies that are lacking operationalised variables to empirically investigate team collaboration, as in (Kuusk et al., 2020) in a recent CoDesign Special Issue on cross-functional collaboration, where the authors noted that their work "lacked prior hypotheses or were not aligned with the traditional structure of an empirical research paper" (Kuusk et al., 2020, pp. 323–324). Four DTRS meetings on teamwork were identified by Christensen and Ball (2019) - DTRS2, DTRS7, DTRS10 and DTRS11 - but using the selection criteria, we included publications from two of these meetings, and excluded the other two, based on inclusion criteria 2 and 6 (see Appendix 1).

2.2 Co-occurrence analysis

For the analysis of the selected literature, we collected bibliometric data of the 17 selected papers from Scopus – the world's largest abstract and citation

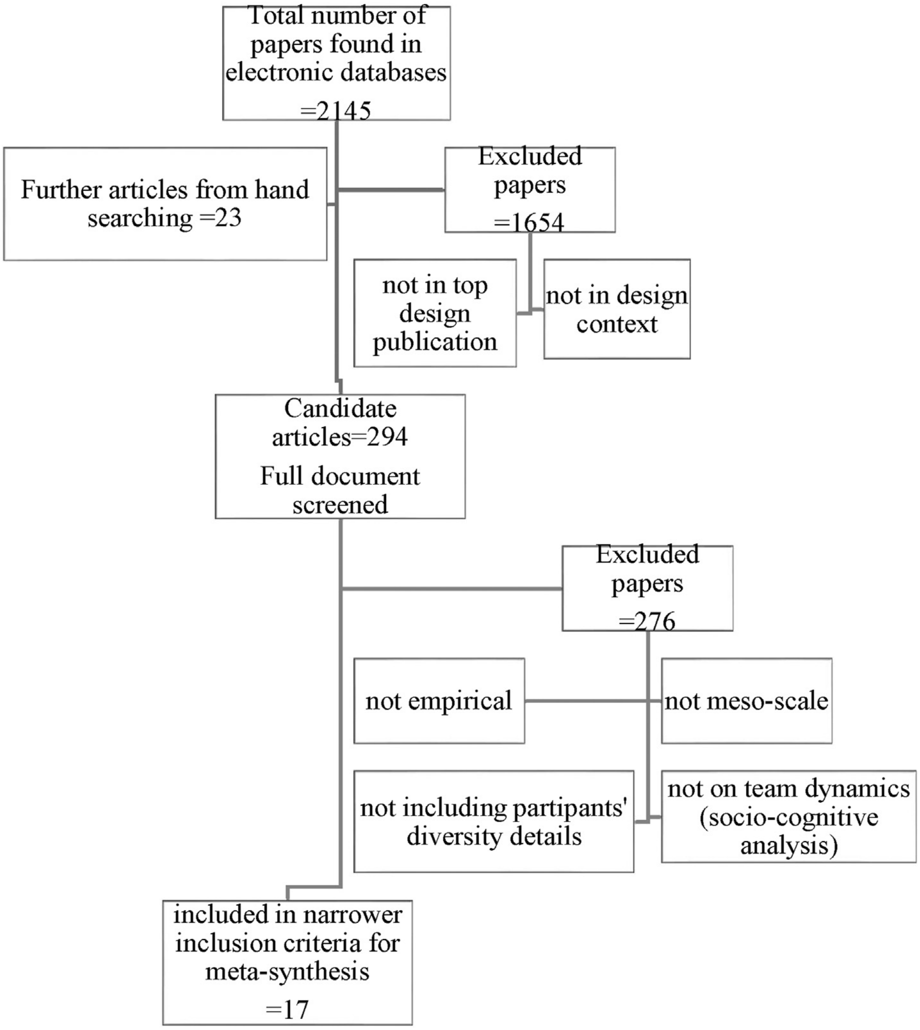

Figure 2 PRISMA diagram for systematic review (based on Moher et al., 2009)

Table 1 Structure of search terms

Practice AND	*Domain* AND	*Participants* AND	*Activity*
multidisciplinary OR transdisciplinary OR interdisciplinary OR cross-functional OR	design	team	collaboration OR teamwork

database. The co-occurrence analysis method enables to construct and visualise a network of emerging themes, i.e. connections within a body of text using linguistic analysis of relationships between words for pattern recognition (Godwin, 2016) and nodes — representations of important terms, their weights

Table 2 Inclusion criteria

No.	*Inclusion criteria*
1	Article must be published in **English**.
2	Article must report findings on **meso-scale (team-level) collaboration**.
3	Article must provide an **overview of the empirical study**
4	Study participants must work in **teams**.
5	Study participants must carry out a **design task** (including engineering design, product design engineering, or architectural design).
6	Authors must identify characteristics of participants in the context of **disciplinary** - functional/professional/ educational - background (task-oriented diversity).

and their location within the network (Van Eck & Waltman, 2014). We employ co-occurrence networks as a supportive tool to reveal patterns that are then further discussed. To perform the text mining functionality and create the term map (see Figure 3), we use VOSViewer applying *natural language processing* (NLP) algorithms (Van Eck & Waltman, 2011). The co-occurrence network has been created with the following steps:

1. Tagging the body of text content through Apache OpenNLP toolkit (identification of *verbs, nouns, adjectives*, etc.),
2. Identification of noun phrases, and converting plural noun phrases into single ones (Linguistic filter: e.g. *team, visualization, design communication,* and *disciplinary expertise*, but not *degrees of freedom* and *highly cited publication*),
3. Selection of the most important noun phrases - the larger the difference between the two distributions (measured using the Kullback-Leibler distance), the higher the relevance of a noun phrase (e.g. low relevance noun phrases: *team, paper, results*; high relevance noun phrases: *expert designer, knowledge, domain*).
4. Grouping of noun phrases with a high relevance into clusters (themes).

In order to unclutter the representation, only the co-occurrences with a high frequency were included in this analysis. For each theme, the size of the label circle and its font size mirror the theme's importance, and their proximities represent classification clusters. These clusters led to five identified theme relationships that are used to guide the qualitative analysis of the core literature.

2.3 Meta-analysis

In addition, we conducted a meta-analysis of the design and variables of each study, using an adapted version of the Collaborative Design taxonomy from Ostergaard and Summers (2009). Table 3 presents the taxonomy classification adopted by the authors, with factors included in the meta-analysis. To address the second part of our research question which focusses on the methodological analysis of design and implementation of the studies, we extended the

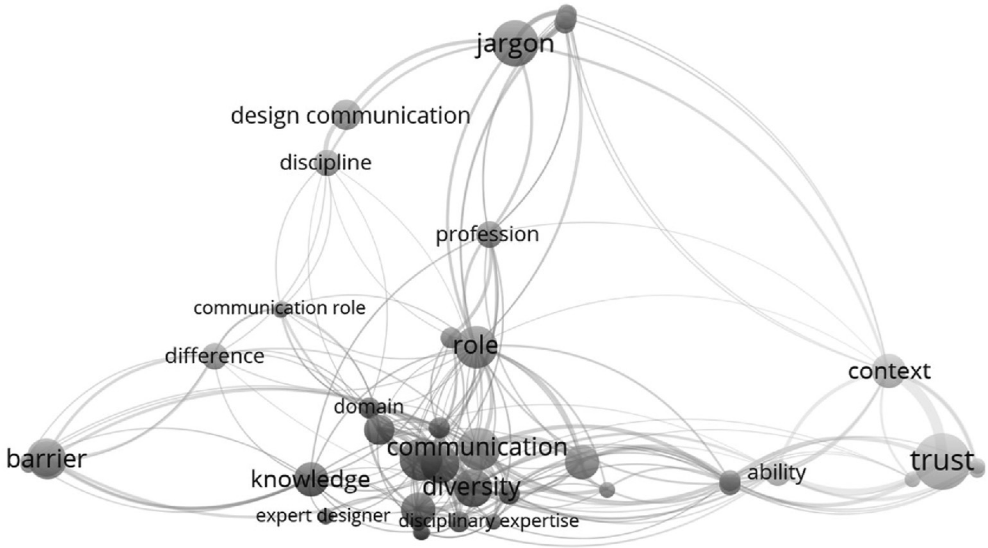

Figure 3 Co-occurrence map of emerging themes

taxonomy with additional variables (the design approach and research methodologies).

3 Findings: 'communication' and other emerging sub-themes

In this section, we address the question of **what** has been studied and found. The co-occurrence analysis of the selected literature shows that these studies address five main themes: Communication, Knowledge and diversity, Trust and context, Barrier and design communication, Jargon and roles. As shown on the co-occurrence network map (Figure 3) constructed from the text mining functionality (see Section 2.2), *communication* is a key component of all the subthemes. Here, we investigate four theme pairs identified through the co-occurrence network map (hence being guided by the terms from the linguistic analysis output), synthesise each of them in the qualitative analysis, and discuss the role of *communication* within these.

3.1 Communication

The analysis of papers reveals that all studies show communication and social interactions as key elements of multidisciplinary design collaboration, as reported below.

Firstly, the co-occurrence analysis highlights that *communication* is a core theme in the selected literature, being linked to and embedded in all other theme clusters. Design is a social process (see Bucciarelli & Bucciarelli, 1994) and social interactions are a critical component of design activity, as

Table 3 Collaborative design taxonomy (adapted from Ostergaard & Summers, 2009)

Factor of the taxonomy	*Sublevel*	*Adapted*
Team composition	Group (size and culture)	included
	Individual (expertise)	included
	Leadership styles (type)	included
Distribution	Personnel	included
	Information	included
Nature of Problem	Abstraction	included
	Complexity	included
Design approach	Duration	added
	Stage	included
Research methodology	Study setting	added
	Sample	added
	Type	added
	Industry	added

they account for 21% of the conceptual design activity time (Austin et al., 2001). Sonnenwald (1996) even suggests that interpersonal talks may facilitate discovery of other participants' perspectives, which can lead to establishing personal bonds. This suggests that shared ownership over design outcomes within a multidisciplinary team can be created through communication and social interactions. In fact, the dynamics of interpersonal relations in design meetings, involving the mutual regulation of tensions and affects, has a significant effect on the efficiency of the collaboration and on the quality of the design outcomes (Détienne et al., 2012). Secondly, scholars looking at design communication find cultural diversity often as critical as disciplinary diversity. Jutraz and Zupancic (2017) explored the differences in communication styles between team members from Asia or from Europe and identify participants' national-specific characteristics as a common communication obstacle. In their study, respondents pointed out that the most challenging part of communication relates to cultural diversity or individual differences, not to disciplinary diversity. A study on design collaboration within teams with East-Asian value orientation (see Taoka et al., 2018) showed that the cultural orientation of the team members, in particular their 'Power Distance' score, affected the quality of collaboration and the level of engagement of the team members. Within our core literature, Zolin et al. (2004) find that such cultural differences result in varying expectations, lower predictability, and following decrease of the trust level. They suggest that the underlying rationale for this can be cultural misunderstandings instead of potential prejudices. In a similar study including Asian - European meetings, D'Souza and Dastmalchi (2017) take on the investigation of language within the cross-cultural design process. Their analysis of slangs used by Eastern and Western participants reveals the different characteristics between these two groups (individual vs. collective, expressive vs. restrained). They also discover the presence of the cultural brokers in the meetings which raises a question on how the design process can overcome barriers from cross-cultural jargon.

Nevertheless, *communication* challenges appear beyond cultural differences; the following sections will discuss the subtheme pairs revealed in the co-occurrence analysis that oscillate around the central notion of *communication* in multidisciplinary design collaboration.

3.2 Knowledge and diversity

Another important theme of the literature highlighted by the co-occurrence analysis is *knowledge and diversity,* which relates to the diversity of knowledge and experience associated with one's disciplinary background. In all studies, authors define teams involved as multidisciplinary or interdisciplinary. We find that none of the common classification taxonomies was used to differentiate the disciplinary distinctiveness. As a result, many of the participants were derived homogeneously from creative backgrounds; they were often arranged with or simulated by designers and design-related professionals. In order to tangibly disseminate the specific disciplines, we analysed the disciplinary background of individual team members in the studies following the Classification of Instructional Programs (CIP)[1] (50.04 Design and Applied Arts; 11.01 Computer and information sciences; 04.02 Architecture; 14.01 Engineering; 52.01 Business/Commerce) and defining *industrial experts* as consulting professionals (such as doctors, nurses) and *end users* such as users of the designed outcome. While all studies define teams involved as *multidisciplinary*, we found that the level of disciplinary diversity is very heterogeneous across the selected literature, two studies even involving one single discipline (Table 4), other studies assigning artificial roles to simulate multidisciplinarity. The details of the disciplinary profile of the teams involved in these studies is discussed below.

In the study of Awomolo et al. (2017) with cross-functional teams, 5 out of 8 team members belong to the design team, and 3 other external consultants include: a market researcher, design researcher, and a design thinking expert; meaning that 7 out of 8 participants are from the same design background. In another study by Kleinsmann et al. (2012) specific roles (energy expert, culture expert, health expert and landscape architect) were assigned to the participants, however all participants were students recruited from *design* courses and professionals with *design* backgrounds. Similarly, the sample from the study of Hu et al. (2017), defined as multidisciplinary, involves graduate students from various *design* specialties. Overall, most participants in the core

Table 4 Multidisciplinarity of the design team

First author, year	*Disciplinary background (as in CIP classification)*					*Industrial expert*	*End user*
	Designer	*Architect*	*Engineering/ Construction*	*Business*	*Computer Science*		
Adams et al. (2009)			X	X			
Austin et al. (2001)		X	X	X			
Awomolo et al. (2017)	X					X	
D'Souza & Dastmalchi, 2017	X					X	
D'souza and Dastmalchi (2016)	X	X				X	
Feast (2012)	X	X			X	X	X
Haines-Gadd et al. (2015)	X		X				
Hu et al. (2017)	X				X		
Jutraz and Zupancic (2017)		X	X	X			
Kasali and Nersessian (2015)	X		X			X	X
Kleinsmann and Valkenburg (2008)	X			X	X	X	
Kleinsmann et al. (2012)		X				X	
Kokotovich and Dorst (2016)	X	X				X	
McDonnell, 2009		X					X
Sonnenwald (1996)	X		X				X
Wang et al. (2018)	X		X	X		X	
Zolin et al. (2004)		X	X				

literature come from design, architecture, and engineering (Table 4), which, when mapped onto the epistemologically framed Becher—Biglan knowledge disciplinary typology (see Becher, 1989; Coughlan & Perryman, 2011), all belong to the category *Hard Applied*. Similarly, participants in the research of Kokotovich and Dorst (2016) and D'souza and Dastmalchi (2016) come from art, architecture, psychology, journalism and english — all of which belong to the *Soft Pure* category in Becher's classification. Specifically, while Kokotovich and Dorst (2016) note that design teams consisting solely of designers have very similar perspectives and heuristics, all participants in their study had a background in *art*, as defined by the American National Endowment for the Arts,[2] and were considered creative (see Amabile et al., 1996).

A truly multidisciplinary team has been employed in a study on design team boundaries (Adams et al., 2009), where participants were from mechanical engineering, industrial design, ergonomics and business. The study revealed significant challenges related to differences in disciplinary-related languages and world views, and further suggested that cross-boundary practices are less related to synthesising participants' areas of expertise, but refer more to crossing their perspectives, broadening the disciplinary knowledge with language, roles, or social interactions.

Multidisciplinary collaboration also happens when end-users are involved, as in many *codesign* studies (see Sanders & Stappers, 2008), and take part in design meetings as *experts* of their disciplines (Adams et al., 2009; Feast, 2012; McDonnell, 2009; Sonnenwald, 1996). Adams et al. (2009) involve experts with a minimum of fifteen years of experience, including architects and designers and end-user professionals such as doctors, nurses, engineers, or hospital managers. In Sonnenwald (1996), the communication between software engineers, software designers and *end-users* - who are salespeople and client's office staff – is analysed. The study identified communication roles that enabled the team to collectively integrate multidisciplinary knowledge and to form boundary-spanning activities. McDonnell (2009) investigates the conversations between architects and building users, in which she discovers blurred boundaries between the participants' argumentations. Similarly, Jutraz and Zupancic (2017) suggest that the roles for users (expert practitioners in healthcare, in their study) and design experts overlap, therefore they argue to consider *user* participants as additional domain experts.

3.3 Trust and context

The analysis of the trust-context theme shows that knowledge sharing behaviour and trust creation appear to be established in the face-to-face context. Our theoretical analysis of the thematic pair of *trust and context* raises further questions about future *communication* challenges that can emerge, not only due to diverse disciplinary background, but also due to cultural differences and geographical distribution of the design teams. Details of the analysis are provided below.

A study of Haines-Gadd et al. (2015) highlights the importance of trust in multidisciplinary collaboration. In fact, trust is found to be a critical component in cross-functional teamwork (Zolin et al., 2004). In terms of disciplinary backgrounds, respondents claim that they would trust professionals from the same domain and expertise more than from other professions. Even without the respect of one's disciplinary background, Feast (2012) reveals that bringing an outsider to an existing group, where participants' roles have been established, creates distrust and further misunderstanding of the group's motivations.

An aspect affecting multidisciplinary teams' trust is the contextual knowledge convergence that enables mutual agreements between participants to take place and create shared understanding. Feast (2012) highlights that collaboration is needed to capitalise on the strengths of different stakeholders to develop shared knowledge and to better deal with the complex combinations of interacting activities, behaviours and relationships that affect design work. This has also been emphasised in the study of Hu et al. (2017), who suggest that more frequent knowledge sharing behaviour, together with the complex sharing network, led to faster mindset shifting from one discipline to another. McDonnell (2009) defines shared understanding to be created through conversation during the design negotiations. Such exchange allows experts to express their non-expert knowledge, which in turn invites the end user to draw on their expert knowledge and thus gain a better understanding of the design context.

Apart from varying domain-related perspectives and regional/national cultures, geographical distribution (and resulting lack of face-to-face interaction) plays a great role in decreasing the level of trustworthiness between participants. Direct, in-person meetings increase the trust between participating members, which results in higher creativity and quality of the work (see Aurisicchio et al., 2010; Gloor et al., 2012). Consistent with this, Kleinsmann and Valkenburg (2008) find that shared understanding is dependent on the face-to-face team communication, project management and project organisation, and geographical dispersion considerably influences the level of team trustworthiness (Zolin et al., 2004).

3.4 Barrier and design communication

The analysis of the thematic pair *barrier and design communication* reveals a crucial role of visual representation in bridging *communication* boundaries. However, some studies provide evidence that these can still be misunderstood by team members from different disciplinary backgrounds. Apart from expertise, intrinsic motivations and personalities are other components affecting creativity (see Amabile, 1988). Personality characteristics provide independence, idea-generating skills and enable taking new perspectives on the problem. Group cohesion is thus affected by motivations, world views, egos and clashing personalities (see Goldschmidt, 1995). Similarly, the lack of group cohesion and confrontational attitudes are challenged with differing personalities (Austin et al., 2001). Feast (2012) highlights that such conflicts influence teamwork so much, as they can lead to one-sided collaboration, when a participant's ego is being intimidated or when she/he receives less responsibility than expected.

Several research papers suggest visual representations as a bridging medium between team communication barriers (see Badke-Schaub & Frankenberger, 2004). Schön (1983, p. 80) notices that design collaboration occurs on the foundation of verbal and non-verbal components, where "drawing and talking are parallel ways of designing and together make up" the *language of designing*. In our core literature, design communication with visual representations emerges as both a facilitating and bridging medium between disciplinary barriers. Adams et al. (2009) state that non-verbal activities, including gestures and drawings, act as communication between the group members, supporting multidisciplinary collaboration. They manage to build on each other's ideas in the forms of such visual representational practices. Consistent with this, Kasali and Nersessian (2015) suggest that design drawings are critical in developing cross-domain expertise. Such drawings are thus defined as a synthesis of multidisciplinary knowledge. They suggest that beyond the verbal interaction, these visual representations act as key roles in translating and blending differing professional expertise. This enables multidisciplinary assessment in the group, leading to later consensus among the participants. McDonnell (2009) highlights that the visual representations play an important role in defining the routine for internal interactions, helping to organise the discussions' themes to comply with interests of all the participants. These sketches become a common reference point for organising the conversation order, importantly without imposing a rigorous structure for such discussions. Notwithstanding, one might claim that quick sketches acting as a bridging medium, require a pre-established shared understanding in the collaboration (Feast, 2012). Similarly, a study from Kleinsmann and Valkenburg (2008) supports this finding, when an electrical engineer created an explanatory drawing for the ergonomist however they were still not able to productively negotiate with one another a solution for the problem.

3.5 *Jargon and roles*

As shown earlier, multidisciplinary design collaborators often face communication challenges. This section shows that the use of different jargons – or disciplinary languages – is a source of difficulties in communication and that the allocation of specific roles may help overcome these difficulties. Kleinsmann and Valkenburg (2008) suggest that on the team communication level, the difficulties emerge due to differences of the jargon used by the participants, different design representations and responsibilities. Similarly, the importance of design jargon issues was highlighted by D'Souza and Dastmalchi (2017). Hu et al. (2017) define different jargon as unique, specialised work languages together with different past experiences, work patterns, quality and success perception, organisational priorities, and technical constraints. High constructive interactions foster productive creation of good ideas and promote idea integration and co-building. One person contributes from his/her discipline expertise, inviting the other to respond and supply information with the provoked expert response (McDonnell, 2009). This, however, requires the recognition of others' expertise and appropriately timed assertion of such expertise, in order to reach consensus.

Considering these aspects, the differing jargon used in multidisciplinary design meetings relates to their disciplinary and cultural background diversity. Social interaction and frequent constructive interactions can facilitate resolving possible communication tensions. To overcome jargon conflicts through encouraging discussion, stimulating imaginations and negotiating ideas, team roles act as a collaboration facilitator. Renegotiation of the earlier defined roles emerges as a feature of social integration during the design talks (McDonnell, 2009). Feast (2012) defines collaboration as a social activity that is affected by the participants' responsibilities and roles (that do not represent their domain-related expertise). As responsibilities relate to one's role in a team, many research articles attempted to classify these roles for multidisciplinary collaboration (see Lloyd, 2000; Moore, 2006; Stempfle & Badke-schaub, 2002).

We reviewed two classifications of roles and reported their findings in Table 5. Sonnenwald (1996) suggests 13 communication roles for multidisciplinary teams, that are categorised according to the boundary type they resolve. These boundary-spanning roles are supposed to support knowledge integration and collaboration, together with negotiating differences across discipline and personal boundaries. Adams et al. (2009) define eight emerging roles that work as triggers in shifting cross-disciplinary conversations. Their research also finds that frequent switching of roles correlates with the non-hierarchical nature of the meetings. In the instance where there is no end-user involved in the group, the role of the 'Storyteller' suggests that understanding the user becomes a meeting point, where team members can build a shared understanding of the problem. They highlight how people mediate cross-disciplinary practices by bridging and synthesising multiple perspectives. These two classifications of roles overlap for two major functions: *Intergroup star <> Facilitator*, as managerial and planning functions, and *Interdisciplinary star Intradisciplinary star/Environmental scanner <> Informer,* as domain-specific knowledge transmission functions. Sonnenwald (1996) findings lack many roles specifically designed for the ideation process facilitation, whereas Adams et al.'s (2009) investigation looks mainly at the ideation process of the teamwork. It is thus unclearwhat the best practices are regarding the suggested roles for the teamwork in design. Moreover, there is a requirement of time needed to clarify and establish such roles, as they are unclear in the early stages of collaboration. When the roles are not agreed and defined, later problems may occur (Jutraz & Zupancic, 2017). In their study, such lack of mutual agreement on roles led to unbalanced decision-making responsibilities. As a result, the team spent 1 or 2 weeks working additionally before reaching the joint decision. Similarly, McDonnell (2009) points out in her findings, the importance of appointing one's role *a priori*, and later renegotiating it during the design meetings.

Although there have been several attempts to identify specific roles within design meetings, there is still a lack of consensus in this area. Further meta-

Table 5 Mapping of group roles from (Sonnenwald, 1996) and (Adams et al., 2009)

Boundary type	*Sonnenwald (1996)*		*Adams et al. (2009)*	
	Role	*Description*	*Role*	*Description*
Organisational boundaries	Sponsor	secures acceptance and funding in the larger organisational unit and external unit.	–	
	Interorganisational star	interacts with others in a larger organisational unit(s) and external unit(s) to ensure a match with the design project goals and strategies.	–	
	Intergroup star	plans and co–ordinates activities across groups and represents their group in planning discussions.	**Facilitator**	directs and manages the meeting, which is observed to be playing a crucial role in multidisciplinary environments.
	Intraorganisational star	filters and transmits organisational project information across hierarchical organisational levels within the design project.	–	
	Intragroup star	facilitates interaction among group members.	–	
Task boundaries	Intertask star	facilitates interaction and negotiates conflicts between people doing different design tasks.	–	
	Intratask star	facilitates interaction, and co–ordinates activities, within a task.	–	

(*continued on next page*)

Table 5 (*continued*)

Boundary type	*Sonnenwald (1996)*		*Adams et al. (2009)*	
	Role	*Description*	*Role*	*Description*
Discipline boundaries	**Interdisciplinary star**	integrates knowledge from different disciplines and domains to create solutions to design problems.	**Informer**	brings external information to the meeting. Interestingly, this is the only role observed to be domain-specific.
	Intradisciplinary star	transmits information about new developments within a discipline.		
Multiple span boundaries	**Environmental scanner**	transmits information from outside the design context, but relevant to the design context, to design participants.		
	–		User Contextualiser	integrates the knowledge about the users internally and externally.
	Mentor	filters and transmits career information to individuals.	–	
	Agent	facilitates interactions and arbitrates conflicts among all design participants.	–	
Personal boundaries	Interpersonal star	facilitates interaction among individuals.	–	
Ideation boundaries	–		Evaluator	judges the ideas discussed and identifies a need to conduct an evaluation.
	–		Idea Generator	presents new ideas.
	–		Interpreter	clarifies a concept or idea presented.
	–		Questioner	raises questions not brought up in the conversation.
	–		Storyteller	contextualises an idea or clarifies an idea by telling a story and enables including knowledge about the use and users.

analysis of the studies design will support our endeavour in understanding such differences.

3.6 Summary of findings

As a conclusion, our analysis has revealed heterogeneity and, at times, conflicts in findings on multidisciplinary collaboration around *communication* in design teams:

- ***Knowledge and diversity***: not all studies employed multidisciplinary teams, where often disciplinary backgrounds were artificially simulated by participants from the same university degree,
- ***Trust and context***: establishing trust requires face-to-face meetings, that can be hindered in geographically distributed teams,
- ***Barriers and design communication***: visual representation and drawings act as a bridging medium in design communication, but can still be misunderstood by team members from other disciplinary backgrounds,
- ***Jargon and roles***: assigning specific roles may improve communication challenges related to jargon differences, yet studies have no clear classification of such roles due to different study designs.

4 Meta-analysis: variables manipulated in the studies

To better understand how previous studies have been designed and why such diversity in the findings occurred, we further analysed the selected literature and reviewed the designs and variables of these studies by using a taxonomic classification of factors that influence collaborative design (Ostergaard and Summers (2009): team composition (size, culture, expertise level, leadership), distribution, nature of problem, design approach and research methodologies). We present in the following summary tables, methodological details of these research articles, with each row corresponding to one publication ("X" indicates where a variable was assigned a particular value. "?" indicates where it was not feasible to identify the value assigned to a variable).

4.1 Team composition

On an individual level, team composition characteristics are commonly manipulated variables in the study designs. Table 6 depicts the characteristics of the team composition in terms of size and culture in the core literature.

The investigation on the heterogeneity of teams involved brings into light the potential cultural differences among team members, where many studies consist of culturally heterogeneous groups (Awomolo et al., 2017; D'Souza & Dastmalchi, 2017; Jutraz & Zupancic, 2017; Zolin et al., 2004). Research has shown that such cultural diversity increases the risk of communication

Table 6 Team composition: size and culture (adopted from Ostergaard & Summers, 2009)

Authors, year	Size			Total study size	Culture	
	small	medium	large		cross-culture	homogenous
Adams et al. (2009)		X		9	?	?
Austin et al. (2001)	X			15	?	?
Awomolo et al. (2017)		X		8	X	
D'Souza & Dastmalchi, 2017		X		8	X	
D'souza and Dastmalchi (2016)		X		7		X
Feast (2012)	?	?	?	23	?	?
Haines-Gadd et al. (2015)	?	?	?	?	X	
Hu et al. (2017)		X		17	?	?
Jutraz and Zupancic (2017)		X		?	X	
Kasali and Nersessian (2015)			?	16	?	?
Kleinsmann and Valkenburg (2008)		X		50	?	?
Kleinsmann et al. (2012)	X			9 teams		X
Kokotovich and Dorst (2016)		X		?	?	?
McDonnell, 2009	X			4	?	?
Sonnenwald (1996)			X	15	?	?
Wang et al. (2018)		X		257	?	?
Zolin et al. (2004)	X			108	X	

issues and cultural barriers. Zolin et al. (2004) find that cultural diversity has a strong impact on decreasing trustworthiness between the group participants. In another study, respondents admit that cultural barriers are more challenging than discipline-related differences (Jutraz & Zupancic, 2017). One of the issues reported by D'Souza and Dastmalchi (2017) was the varying jargon that is used by members from different cultures.

Additionally, Feast (2012) argues that the number of participants is another valid contributor. Group size plays an important component in the scientific research of teamwork (see earlier investigations by Shaw, 1932). For the purpose of this review, we use the group S*ize* parameter with 3 levels defined originally in the team research theory (Klein et al., 2009):

- *small* with less than 5 members
- *medium* with 5–10 members
- *large* with more than 10 members

Most studies in the core literature consist of studies employing small and medium groups with only one study related to a group greater than 10 members. Feast (2012) emphasises that team size will considerably affect the collaborative level of the group. One person can easier influence the small team, whereas in larger teams, the more distributed workload results in lesser ownership from an individual. Wang et al. (2018) suggest limiting the team to 6 participants, in order to evenly distribute the expertise within a multidisciplinary team. However, findings based on one small sample size risk external invalidity (Yin, 1984). Explicitly, Kleinsmann et al. (2012, p. 503) address this limitation in their article, and point out that “therefore, the findings cannot be empirically generalised”.

We can therefore investigate the *total study size* as a more holistic parameter to understand the feasibility of the papers’ findings. The optimal size of research groups for *art and design* studies is 25 ± 8 (Kenna & Berche, 2011). They suggest that, above this size, the quality of the study does not increase significantly. More than half of the papers in our review belong to the recommended study size. Overall, team characteristics, including its size and cultural diversity, play a great role in multidisciplinary collaboration, making a considerable impact on communication between the group members. While group size may influence its cohesion, it also seems to impact the validity of the findings from conducted experiments themselves. We follow our meta-analysis of team composition with the comparison of knowledge experience and leadership factors in the core literature (see Table 7).

Although many studies emphasise the importance of leadership in group work, the role of a project leader tends to be interpreted differently in the literature. Sonnenwald (1996) suggests that one of the responsibilities of a leader is to provide filtering and sharing information about the project’s goals, plans, tasks, and detailed budget information. Consistent with this point, Kleinsmann et al. (2012) describe the project leader’s tasks to be planning and monitoring the design process and costs. An important aspect of leadership is that while guiding the group through the design activity, there is a risk of the team leader progressing without agreeing the project’s direction

Table 7 Team composition: expertise and leadership (adopted from Ostergaard & Summers, 2009)

First author, year	*Expertise level*				*Leadership*	
	novice student	*senior student*	*novice professional*	*senior professional*	*Yes*	*No*
Adams et al. (2009)			?	?	?	?
Austin et al. (2001)			X	X	X	
Awomolo et al. (2017)				X	X	
D’Souza & Dastmalchi, 2017				X	X	
D’souza and Dastmalchi (2016)	X	X				X
Feast (2012)			X	X	X	
Haines-Gadd et al. (2015)			X		X	
Hu et al. (2017)		X				X
Jutraz and Zupancic (2017)		X			?	?
Kasali and Nersessian (2015)				X		X
Kleinsmann and Valkenburg (2008)			X	X	X	
Kleinsmann et al. (2012)	X	X	X		X	
Kokotovich and Dorst (2016)	X	X			X	
McDonnell, 2009			?	?	X	
Sonnenwald (1996)				X	?	?
Wang et al. (2018)		X				X
Zolin et al. (2004)		X			X	

with the remaining participants (Austin et al., 2001). Therefore, the leader often takes another role and makes the most of the design decisions concerning not only the methodology used in the meeting but also its content (Awomolo et al., 2017). Also, through having multidisciplinary participants, such dominance of the team leader can be reduced. Haines-Gadd et al. (2015) present the idea of the leadership role rotation that becomes an enabler for new collaboration energies to take place at various project stages.

The level of knowledge (experience) might also influence the design process, its outcome and team collaboration. D'souza and Dastmalchi (2016) find that undergraduate juniors can make a significant impact on the design process with an increased number of creative events within it. Contrary to this, the novice team in the study of Kokotovich and Dorst (2016), who did not use any design methodologies or tools, were later unable to both enrich the design solutions space, and did not manage to cross domains nor develop new higher levels of abstractions. The sample of the least experienced participants was represented by students from the undergraduate academic level. In 56% of the observed instances, the team was not operating on the competent level (Dreyfus, 2004), where problem-solving is accompanied with high design situation involvement, emotional involvement, learning and reflection. A lower experience level, described as limited expertise contributed, may lead to inefficient use of time and resources (Haines-Gadd et al., 2015).

In most studies, teams are being formed in laboratory experiments using students from the same academic year or early-career, which is rarely the case in a real-world situation (Wang et al., 2018). An interesting perspective is presented by Sonnenwald (1996), where she suggests that the number of years of professional experience reflects the participant's role within the group. For example, participants with minimal professional experience can take on the roles of interaction facilitators between project members. Participants managing cross-organisational information require more than 8 years of professional experience, whilst those coordinating activities need more than 14 years. It is worth highlighting that the interdisciplinary star who integrates knowledge from different disciplines and domains has a minimum of 10 years of professional experience.

4.2 Distribution

Design process can be significantly affected by the dispersion of the team members. For ease of the analysis, we combine the distribution metrics of both personnel and information distribution and use an overarching category "distribution" for all variety of distribution boundaries, including geographic, organisational, and temporal dispersion (see Table 8).

Table 8 Team distribution (adopted from Ostergaard & Summers, 2009)

First author, year	*Distribution*	
	Collocated	*Distributed*
Adams et al. (2009)	X	
Austin et al. (2001)	X	
Awomolo et al. (2017)	X	
D'Souza & Dastmalchi, 2017	X	
D'souza and Dastmalchi (2016)	X	
Feast (2012)	X	
Haines-Gadd et al. (2015)	X	
Hu et al. (2017)	X	
Jutraz and Zupancic (2017)		X
Kasali and Nersessian (2015)	X	
Kleinsmann and Valkenburg (2008)	X	
Kleinsmann et al. (2012)	X	
Kokotovich and Dorst (2016)	X	
McDonnell, 2009	X	
Sonnenwald (1996)	X	
Wang et al. (2018)	X	
Zolin et al. (2004)		X

As Ostergaard and Summers (2009) suggest, distributed design teams would require exceptional support compared to collocated teams. For example, in the study of Jutraz and Zupancic (2017) there was a significant variety of additional computer supportive tools used to facilitate the design collaboration, including SketchUp, Revit, Skype, GoToMeeting, Brainmerge, Box, Dropbox, GoogleDocs, Terf and others. The authors raised the importance of implementing distributed work in educational courses, in order to improve designers' computer skills and learn about digital programs. Since geographical dispersion influences significantly the level of trustworthiness between team members (Zolin et al., 2004), it may in turn challenge the whole design process (for example, Garner (2001) shows that distributed designers spent 51% more time creating graphic acts than those in collocated teams). However, only 2 studies in the core literature are looking at the distributed design teams. We can hence conclude that, there is still a big gap in previous empirical research in understanding differences and consequences of the geographical distribution of the design meetings.

4.3 Nature of problem

Some aspects of the design problem may also affect the collaborative design. Following our adopted taxonomic classification, we present in Table 9 variables based on the nature of the problem used in the selected empirical studies.

In most of the studies, the participants are being instructed to focus on developing a physical product (adapted as concrete), e.g. buildings, backpack, car accessory for industrial or product design objectives. In one study, Hu et al.

Table 9 Nature of design problem (adopted from Ostergaard & Summers, 2009)

First author, year	*Abstraction*			*Complexity (adapted to design objective)*		
	concrete (physical)	*abstract*	*intermediate (digital)*	*low (product)*	*medium (industrial)*	*high (service)*
Adams et al. (2009)	X				X	
Austin et al. (2001)	X					
Awomolo et al. (2017)	X				X	
D'Souza & Dastmalchi, 2017	X				X	
D'souza and Dastmalchi (2016)			X	X		
Feast (2012)	?	?	?		X	
Haines-Gadd et al. (2015)	X			X		
Hu et al. (2017)		X				X
Jutraz and Zupancic (2017)	X				X	
Kasali and Nersessian (2015)	X				X	
Kleinsmann and Valkenburg (2008)	X				X	
Kleinsmann et al. (2012)		X			X	
Kokotovich and Dorst (2016)			X	X		
McDonnell, 2009	X				X	
Sonnenwald (1996)	X				X	X
Wang et al. (2018)			X	X		X
Zolin et al. (2004)	X				X	

(2017) investigate how the mindset of participants switches from industrial thinking to service thinking. They find that the mindset shifting process is significantly influenced by communication and interactions between the participants. In order to successfully cope with service thinking without previous experience in this domain, participants are required to present frequent knowledge sharing. In a similar fashion, Kokotovich and Dorst (2016) study how designers can move from traditional concepts towards a higher level of abstraction. Their investigation of the project, that resulted in a website for the cards industry (digital product), suggests that multidisciplinary teams have difficulties in crossing domains and could not develop higher levels of abstractions. Bearing that in mind, 65% of the design outcomes are physical products, and in only 3 scenarios the resulting product is digital (D'souza & Dastmalchi, 2016; Kokotovich & Dorst, 2016; Wang et al., 2018). Considering these studies, the discourse of multidisciplinary collaboration raises limited understanding of issues related to the nature of digital outcomes and those with high levels of abstraction and complexity.

4.4 Design approach

As with the disciplinary background of the participants, the literature body varies in the examination of the participants' work type and the design process itself. Table 10 shows variables for design approaches investigated in the core literature.

The majority of the selected studies refer to conceptual work, and only 3 studies describe the prototyping phase. Notwithstanding, it was found by

Table 10 Design approach (adopted from Ostergaard & Summers, 2009)

First author, year	*Stage*		*Project duration*		
	conceptual design	*prototype*	*short (day)*	*medium (<month)*	*long (>month)*
Adams et al. (2009)	X		X		
Austin et al. (2001)	X			X	
Awomolo et al. (2017)	X				X
D'Souza & Dastmalchi, 2017	X				X
D'souza and Dastmalchi (2016)	X			X	
Feast (2012)	?	?			X
Haines-Gadd et al. (2015)	x	X			X
Hu et al. (2017)	X			X	
Jutraz and Zupancic (2017)	X				X
Kasali and Nersessian (2015)	X	X			X
Kleinsmann and Valkenburg (2008)	X				X
Kleinsmann et al. (2012)	X		X		
Kokotovich and Dorst (2016)	X	X		X	
McDonnell, 2009			?	?	?
Sonnenwald (1996)	X				X
Wang et al. (2018)	X		X		
Zolin et al. (2004)	X				X

Haines-Gadd et al. (2015) that prototyping is instrumental in the design process by decreasing mistakes and improving the design. They suggest that prototyping can be utilised as tools for communication and integration between the participants. The idea is supported by the research of Kasali and Nersessian (2015), who find that prototypes are critical in bringing together the differentiated expertise within the multidisciplinary teams.

Additionally, an interesting aspect of the design process is the duration of the projects. We note that most empirical cases are spread across a longer period of the design collaboration (over a month), and only 3 refer to one-day projects.

4.5 Research methodology

With an increasing need for domain-crossing collaboration, the issue of multidisciplinary teamwork has generated appeal among academic work. Nevertheless, we note that there are differences in methodologies applied by the authors across the empirical studies in this review. We present in Table 11 identified characteristics of the design of selected studies.

As presented in Table 11, out of the 17 core research articles, 8 studies were employing samples of university students. As Kasali and Nersessian (2015)

Table 11 Research methodology across the core literature

First author, year	*Setting*		*Sample*		*Data source*				
	natural	*laboratory*	*university*	*industry*	*Case study*	*Protocol analysis*	*Field observation*	*Interviews*	*Questionnaire*
Adams et al. (2009)	X			X		X			
Austin et al. (2001)		X	X						X
Awomolo et al. (2017)	X			X		X			
D'Souza & Dastmalchi, 2017	X			X		X			
D'souza and Dastmalchi (2016)		X	X			X			
Feast (2012)		X		X				X	
Haines-Gadd et al. (2015)		X		X				X	
Hu et al. (2017)		X	X				X	X	
Jutraz and Zupancic (2017)		X	X		X				X
Kasali and Nersessian (2015)		X		X			X	X	
Kleinsmann and Valkenburg (2008)	X			X	X				
Kleinsmann et al. (2012)		X	X	X		X		X	X
Kokotovich and Dorst (2016)		X	X			X			
McDonnell, 2009		X		X		X			
Sonnenwald (1996)	X			X			X	X	X
Wang et al. (2018)		X	X						X
Zolin et al. (2004)		X	X						X

notice, there has been little research into how interdisciplinary teams operate in the real world and how the multitude of professionals communicate and integrate their expertise. Only 5 studies in the core literature were carried out in a natural setting (conducted in a non-experimental nature), meaning over 70% of the research articles involve experiments in a laboratory setting, highly correlated with the employment of student participants (60% of them with university samples).

In design studies, protocol analysis has been gaining much attention in the last quarter of the century (Dorst, 1995). The design research community widely employs this approach in order to measure not only the quantitative metrics but also to capture the thinking processes of the examined participants. It enables the researchers to analyse the design process as a sequence of events in time. This holistic approach is reached by involving protocol coding of video recordings and the following verbatim transcripts. Additional information from notes, sketches or screen captures are also included in the later synthesis to analyse the creative processes in the meetings. Unsurprisingly, protocol analysis is the most popular method within the core literature, with over 40% of studies applying this method for their investigations (Adams et al., 2009; Awomolo et al., 2017; D'souza & Dastmalchi, 2016; D'Souza &

Dastmalchi, 2017; Kleinsmann et al., 2012; Kleinsmann & Valkenburg, 2008; Kokotovich & Dorst, 2016; McDonnell, 2009). Notwithstanding, Feast (2012) observes that protocol analysis still has limitations for examining the collaborative design activity. They argue that it relies too heavily on the problem matter to be solved in a laboratory environment within hours of the session.

Apart from protocol analysis, researchers in the core literature also employ case studies (Jutraz & Zupancic, 2017; Kleinsmann & Valkenburg, 2008). We use the case study as an umbrella term for investigations of a particular phenomenon - *sauté* — in uncontrolled environments. Kleinsmann and Valkenburg (2008) use, more specifically, the learning history method based on storytelling. Since storytelling supports the process of relating events to each other, it is considered to be beneficial for design research. Another method used in the core literature is field observation (Hu et al., 2017; Kasali & Nersessian, 2015; Sonnenwald, 1996), that requires going out into the *field* (Robson & McCartan, 2016) and performing ongoing behavioural observation of the sample. It is worth highlighting a wholesome approach taken by Hu et al. (2017), as they combine spot observation and interviews to gather the data involving all original sketches and documents, real-time dynamic observation, and self-reflective opinions. Interviews have also been used by other authors (Feast, 2012; Haines-Gadd et al., 2015; Hu et al., 2017; Kasali & Nersessian, 2015; Sonnenwald, 1996) with a similar number of studies using questionnaires (Austin et al., 2001; Jutraz & Zupancic, 2017; Sonnenwald, 1996; Wang et al., 2018; Zolin et al., 2004). Where the latter one has a considerably lower cost to perform, interviews provide a lower bias from the respondent (Robson & McCartan, 2016), which can be more fruitful when studying design processes and related team dynamics.

Most studies in the core literature have been performed within the construction industry (see Table 12). We classify under this industry conjointly: architecture, construction, and engineering; studies within such efforts engage over 70% of the analysed literature body.

Specifically, most of the research papers focus on architectural practices (Adams et al., 2009; Austin et al., 2001; D'souza & Dastmalchi, 2016; Feast, 2012; Jutraz & Zupancic, 2017; Kasali & Nersessian, 2015; McDonnell, 2009; Sonnenwald, 1996; Zolin et al., 2004). Healthcare and manufacturing constitute 17% each of the literature body. Only two studies include investigations within software development (Sonnenwald, 1996; Wang et al., 2018). Overall, the studies indicate the increasing need to employ design practices into industries, previously considered as non-design practices. According to the literature, participants from the software department or any mechanical-oriented divisions create barriers in the multidisciplinary collaboration, as they employ different development processes while using different jargon and different representations of the design (see Kleinsmann & Valkenburg,

Table 12 Industrial mapping of the core literature

First author, year	*Area of industrial application*			
	construction	*manufacturing*	*healthcare*	*software*
Adams et al. (2009)	X			
Austin et al. (2001)	X			
Awomolo et al. (2017)	X			
D'Souza & Dastmalchi, 2017	X			
D'souza and Dastmalchi (2016)		X		
Feast (2012)	X			
Haines-Gadd et al. (2015)			X	
Hu et al. (2017)	?	?	?	
Jutraz and Zupancic (2017)	X			
Kasali and Nersessian (2015)	X		X	
Kleinsmann and Valkenburg (2008)		X		
Kleinsmann et al. (2012)	X			
Kokotovich and Dorst (2016)		X		
McDonnell, 2009	X			
Sonnenwald (1996)	X			X
Wang et al. (2018)		X	X	X
Zolin et al. (2004)	X			

2008). On the contrary, architects can draw on their experiences from design nature, and act as mediators between varying professionals (Jutraz & Zupancic, 2017), as well as enablers for efficient collaboration, by setting out the right processes. As a result, the disciplinary background of participants seems to directly impact the results of the experiments, and research has been equivocal in terms of the generalisation of findings on multidisciplinary collaboration.

A synthesis of all variables used in the meta-analysis (Table 13) shows that most studies in the reviewed literature examined design activities which lead to physical outcomes ("Design outcome") and on collocated teamwork ("Distribution"); also, most studies are conducted in laboratories ("Setting") and nearly half of them rely on student sample participation ("Participants"). These results are discussed in section 5.2.

5 Discussion

This section presents the main findings from the review: the identification of the importance of 'shared understanding' in multidisciplinary design collaboration (5.1), the limited generalisability of reviewed studies (5.2), their limited methodological rigour (5.3) and their low industrial relevance (5.4).

Table 13 Synthesis of variables presented in the meta-analysis of the selected literature

Variable	*Parameter*	*% total**	*Variable*	*Parameter*	*% total**
Participants involved in studies			**Studied design activity**		
Participants	Industry	53	Distribution	Collocated	82
	University	47		Distributed	18
Background	Industrial expert	19	Duration	Short (day)	19
	Engineering	17		Medium (<month)	25
	End user	9		Long (>month)	56
	Designer	23	Objective	Industrial	61
	Computer Science	6		Product	22
	Business	11		Service	17
	Architect	15	Industry	Construction	57
Expertise level	Senior student	32		Manufacturing	14
	Senior professional	37		Healthcare	14
	Novice student	11		Software	14
	Novice professional	21	Design phase	Conceptual design	83
Leadership	Yes	69		Prototype	17
	No	31	Outcomes	Physical product	69
Cultural Distribution	Heterogeneous	71		Digital product	19
	Homogenous	29		Abstract concept	13
Group size (people)	Medium (5−10)	64	**Research methodology**		
	Small (<5)	29	Setting	Laboratory	82
	Large (>10)	7		Natural	18
			Methodology	Protocol analysis	32
				Questionnaire	23
				Interview	23
				Field observation	13
				Case study	9

* example: 82% of the reviewed papers present a study of 'collocated' multidisciplinary design collaboration.

5.1 Importance of shared understanding (from the theoretical synthesis)

Amongst the emerged theme relationships, we can identify prominent areas worth taking a closer look at. Conflicts regarding these aspects are related to disciplinary and perspective variation of the participants, and jargons used by them. Misunderstandings are common in multidisciplinary teams, which is also accentuated by the differences in cultural background, and geographical distribution of the team members. Visual representations appear to be a good bridging medium and facilitator for potential conflicts. However, there is a requirement of an established shared understanding between participants, where knowledge sharing actions are key to overcome design communication barriers (see Section 3).

Our theoretical synthesis, supported initially by the co-occurrence analysis, unearthed specific theme relationships related to the *knowledge diversity and communication*, *trust and context*, *barrier and design communication*, *jargon and roles*. All the emerged themes present challenges of team collaboration, known in extant literature within the research of group cognition. Group level phenomena in an organisational context were studied by scholars using "group-mind" constructs linked to group cognition or team mental models (Klimoski & Mohammed, 1994). Previous literature presents a resurgence of interest in the group cognition across many fields, including human resources (Cannon-Bowers et al., 1993), business policy and strategy (Floyd & Wooldridge, 1992; Reger & Huff, 1993), and organisational behaviour (Cannon-Bowers & Salas, 2001; Mohammed & Dumville, 2001; Walsh et al., 1988; Weick & Roberts, 1993). The notion of mental models was first proposed by Craik (1952) in an attempt to explain human behaviour coping within a complex world, as mental models are used by human beings as internal representations to react to the changing environment. Such dynamic requirements are prevalent in ill-defined design tasks that require non-routine behaviour (Goel, 1995; Simon, 1984). The greater the overlap or commonality in team members' mental models, the higher the team's capacity to develop common expectations of the task, predict team behaviours, and better adapt to the changing demands, whilst improving taskwork coordination.

It is unclear how that affects the notion of shared cognition in the design team, by which reaching too much consensus may cause individuals in the team to hinder creativity. The construct of shared mental models hypothesized hitherto from a perspective of team performance and effectiveness inhibits theorising for team creativity and innovation. Within design studies, we recognise an increasing body of research on shared cognition in design teams, with the construct being introduced in CoDesign in 2007 (Badke-Schaub et al., 2007; Casakin & Badke-Schaub, 2017; Cash et al., 2017, 2020) that therefore sets the path for future research work. To further enrich our understanding of multidisciplinary design collaboration, we may take on the direction of studying the notion of shared cognition in a creative context in reference to the emerged themes and group aspects that have been identified in this presented literature review.

5.2 Low generalisability (from study designs and variables meta-analysis)

By revealing prevalent themes in multidisciplinary design collaboration, we challenge important scholarly assumptions regarding the relationship between them. And due to variation in variables used in the empirical studies, findings include both commonalities and contradictions in some aspects. As shown in Table 13, most studies were conducted in laboratory settings, nearly half of them rely on student focused on design activities which lead to physical outcomes and on collocated teamwork; also, most studies are conducted in laboratories ("Setting"). Lastly, more than 40% of the reviewed studies rely on student sample participation ("Participants").

The scientific community draws attention to taking extra caution with experiments on student samples compared to non-student *adult* populations (Peterson, 2001), and while some consider student-based research externally invalid (Gordon et al., 1986), almost half of the investigated papers in this review are studies of university participants. Additionally, many of the works are laboratory experiments, where the authors have manipulated study variables. This can become a limitation for the external validity of the emerged findings (Robson & McCartan, 2016). Scientific experts do acknowledge this limitation and explain the choice of laboratory student teams plausible for the sake of methodological strictness (Stempfle & Badke-schaub, 2002). They suggest that laboratory experiments can provide some insight into basic thinking processes without being contaminated by unpredictable factors prone to take place in research with an industry context. This, however, must be considered with the highest caution for team collaboration research; though laboratory studies with student participants may be important for work behaviour research at the individual level (Dobbins et al., 1988), Chapanis (1967, p. 564) observed that most laboratory experiments have very limited relevance for practical situation, where "unsuspected interactions in real life may nullify or even reverse conclusions reached in the laboratory".

5.3 *Limited methodological rigour (from study designs and variables meta-analysis)*

We follow our discussion on the limitation concerning the danger of low generalisability not only due to the laboratory setting/student participants, but also due to usage of secondary data in design studies. In a panel debate at DTRS11 in 2017, Gabriela Goldschmidt (in B. Christensen et al., 2017, p. 7) expressed concerns on the lack of the methodological rigour in design research: *"When you use a shared database, you have to have very good reasons to do so. You have to make sure that the particular dataset that you have chosen is really the most suitable way to probe the kind of question that you are interested in, and that is not always what has happened here"*, which is supported by the points raised in our review of literature. Much of the published work and following this, some publications in our core literature, are de facto employing the same data subsets:

- DTRS 11 (Awomolo et al., 2017; D'Souza & Dastmalchi, 2017).
- D'souza & Dastmalchi, 2016; Kokotovich & Dorst, 2016.
- Adams et al., 2009; McDonnell, 2009.

In line with our previous commentary on the lack of agreed methodological rigour in the design area, this limitation emphasises the issue of the methodological quality of the obtained findings. Traditionally, in order to ensure reliability of measures, each data set is designed for a specific research project, and to answer a specific set of research questions. Employing secondary data, in turn, would affect the process of data collection and sampling, and the risk unfolds when the meta-information is insufficient, which in turn increases the risk of lower reliability and validity (Hox & Boeije, 2005) of the used procedures.

5.4 Low industrial relevance (from study designs and variables meta-analysis)

This literature review is an important starting point in defining how to develop tools for collaboration in the realms of the current innovation-led economy. A report from McKinsey & Co (Sheppard et al., 2018), shows that the use of design practices and business performance is positively correlated across a wide range of industries, and that design practices are beneficial for the development of physical goods, digital products and services, or a combination of these. Moreover, team collaboration discourse is undergoing a remarkable revolution, as its virtual factor has become a widespread common practice in companies of all industries. At Alphabet\Google, one of the top 5 most innovative companies from the BCG 2019 annual report (Ringel, 2019), 100 000 employees are spread out over 150 cities across more than 50 countries. According to industrial surveys, remote work will continue to be one of the main challenges in the post COVID-19 public realm (see IBM Institute for Business Value & Oxford Economics, 2021, February).

Another aspect is the increase of service and digital product design over the last decades. Companies producing hardware products are alongside developing innovative digital applications. The companies on the referred most innovative list (Ringel, 2019) — especially those in the top ten — offer digital products including operational systems (iOS), cloud platform products and solutions (AWS), or digital advertising (Google Ads). However, our meta-analysis reveals that there is limited evidence for theorising specifically in the context of distributed collaboration, as well as abstract design outputs (see Table 13). In addition to design practices, leaders from these most innovative companies have extensively referred to the importance of team collaboration in the innovation design processes: "[…] software innovation, like almost every other kind of innovation, requires the ability to collaborate and share ideas with other people" explained Microsoft co-founder Bill Gates (BBC, 2007) or "My model for business is The Beatles. […] That's how I see business: great things in business are never done by one person, they're done by a team of people" - Apple co-founder Steve Jobs (Isaacson, 2011). Nevertheless, there are little efforts from the management academia to include design as part of their portfolio (Cash, 2018). Our meta-analysis of design studies accentuates and makes salient the need for higher rigour and standardisation of design research methodologies. Such discrepancies in the employed research designs and chosen empirical study settings may result in low generalisability of design research to a wider literature, inhibiting further theorising on design collaboration.

5.5 Limitations

We acknowledge that traditional analysis tends to be performed with a single unit of analysis. However, to consider the methodological differences and explore team composition variables used by the authors in team-related works, we followed a multilevel approach (Gong et al., 2013) by crossing the levels of analysis. Namely, this type of analysis, widely discussed by Hackman (2003) enabled us to look at how teams are affected by their multidisciplinary design and how, on the micro-level, individuals' background affects such collaboration. Hackman (2003, p. 907) suggests that social and organisational dynamics require attention to both lower and higher level of analysis through the process of bracketing that can: "(1) enrich understanding of one's focal phenomena, (2) help one discover non-obvious forces that drive those phenomena, (3) surface unanticipated interactions that shape an outcome of special interest, and (4) inform the choice of constructs in the development of actionable theory".

Moreover, co-occurrence analysis is a unique method for literature reviews, gaining interest in recent years (Godwin, 2016). Due to the text mining nature of the process, conventional analysis would require more data points. The network analysis has complimentarily supported us in unearthing the weights and relationships of the themes, not possible to visualise in the traditional review methodology. We adopted the co-occurrence network on our small base of the selected literature and hence, treat this solely as a preliminary guide and prerequisite to the following in-depth interpretative theoretical synthesis.

6 Conclusion and future research

Design collaboration can be hampered by communication challenges in diverse teams where there is a lack of shared understanding, whether through language variation or jargon idiosyncrasy, prevalent in multidisciplinary collaboration. The aim of this literature review is to help researchers in the field to interpret previous studies and position their own work. This paper contributes towards a better understanding of the ways multidisciplinary design collaboration has been studied, in particular (1) ***what** has been studied and found and (2)* ***how** studies have been designed and implemented*. The objective is to clarify current challenges in the field and suggest future research directions. This study has reviewed empirical cases of multidisciplinary design collaboration, identified the main patterns within findings, and investigated study designs, their variables, and discrepancies between them. Although we followed a classification scheme, our analysis suggests the need for greater rigour in the study of multidisciplinary design collaboration. In addition, we have elaborated on the underlying mechanisms of multidisciplinary design collaboration. Our theoretical synthesis reveals the importance of shared cognition in design work and as a subject for future research. Our methodological analysis presents a gap in understanding how design collaboration is affected in distributed work and how design teams create artefacts with digital outcomes. Only 12% of the selected studies investigated multidisciplinary design work of distributed teams (as opposed to co-located) and only 12% examined software design projects (as opposed to the design of physical artefacts). These challenges lead us to conclude that previous studies on multidisciplinary design collaboration, based on select empirical cases, appear to gauge an unbalanced picture of the value of team diversity. We recognise the need to adapt prior assumptions to the changing requirements of design outcome (digital) and settings (distributed) for the sake of future design collaboration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1.

Table 14 Example of excluded publications during the PRISMA process

Publication/DTRS meeting	*Authors, Year*	*Title*	*Exclusion evidence*
Design Studies	Graff et al. (2020)	Perceived analogical communication in design teams: Development and validation of a scale	**Not meso-level, the study is on micro-level** "This study focused solely on the recipients' perception that an analogy was used, and we are not able to say if the recipient interpreted the message correctly".
Design Studies	Cash et al. (2019)	The dynamics of design: exploring heterogeneity in meso-scale team processes	**Not multidisciplinary** "Study on "meso-scale team processes in two engineering design cases (…) As such, while the teams comprised a mix of backgrounds, they both had a distinct engineering focus and similar levels of experience overall".
CoDesign	Jordan and Adams (2016)	Perceptions of success in virtual cross-disciplinary design teams in large multinational corporations	**Not meso-level, the study is on macro-level:** "Results indicate that factors that contribute to success include the context in which teams work, the method by which teams do their work, and the media by which teams communicate".
CoDesign: Special issue: Experiential Knowledge and Collaboration	Kuusk et al. (2020)	A transdisciplinary collaborative journey leading to sensorial clothing	**The research was not empirically designed to study team-dynamics, team aspects were only reflected on in discussion section:** "During the publication process of our results at some conferences and journals we were often criticised for attempting to combine in a single manuscript the findings from each field and, moreover, embedding the description of the collaboration process, which was an important part of the methodology, as reflected in this article. Criticisms included that we lacked a prior hypotheses or were not aligned with the traditional structure of an empirical research paper.".

(*continued on next page*)

Table 14 (*continued*)

Publication/DTRS meeting	*Authors, Year*	*Title*	*Exclusion evidence*
DTRS2	Akin and Lin (1995)	Design protocol data and novel design decisions	**Not multidisciplinary:** "The objective is to study the behaviours of designers using techniques of cognitive psychology in general and protocol analysis in particular".
DTRS7	McDonnell, 2009 Adams et al. (2009)		INCLUDED
DTRS10	Hess and Fila (2016)	The Development and Manifestation of Empathy within Design: Findings from a Service-learning Course	**Not meso-level, the study is on macro-level:** "We provide a visual summary of student designers' empathic design techniques, the interrelation of these techniques, along with implications for how design educators might effectively embed empathy throughout design curricula."
DTRS11	Awomolo et al. (2017) D'Souza and Dastmalchi (2017)		INCLUDED

Appendix 2.

Table 15 List of core literature

Authors	*Title*	*Year*	*Source title*
Adams R., Mann L., Jordan S., Daly S.	Exploring the boundaries: Language, roles and structures in cross-disciplinary design teams	2009	About: Designing - Analysing Design Meetings
Austin S., Steele J., MacMillan S., Kirby P., Spence R.	Mapping the conceptual design activity of interdisciplinary teams	2001	Design Studies
Awomolo O., Jabbariarfaei J., Singh N., Akin Ö.	Communication and design decisions in cross-functional teams	2017	Analysing Design Thinking: Studies of Cross-Cultural Co-Creation
D'Souza N., Dastmalchi M.R.	"Comfy" cars for the "awesomely humble": Exploring slang and jargons in a cross-cultural design process	2017	Analysing Design Thinking: Studies of Cross-Cultural Co-Creation

(*continued on next page*)

Table 15 (*continued*)

Authors	*Title*	*Year*	*Source title*
D'souza N., Dastmalchi M.R.	Creativity on the move: Exploring little-c (p) and big-C (p) creative events within a multidisciplinary design team process	2016	Design Studies
Feast L.	Professional perspectives on collaborative design work	2012	CoDesign
Haines-Gadd M., Hasegawa A., Hooper R., Huck Q., Pabian M., Portillo C., Zheng L., Williams L., McBride A.	Cut the crap; Design brief to pre-production in eight weeks: Rapid development of an urban emergency low-tech toilet for Oxfam	2015	Design Studies
Hu Y., Li Y., Du X.	Thinking in interdisciplinary design teams based on workshop	2017	Design, User Experience, and Usability: Theory, Methodology, and Management
Jutraz A., Zupanic T.	The Role of Architect in Interdisciplinary Collaborative Design Studios	2014	Igra ustvarjalnosti - Creativity Game
Kasali A., Nersessian N.J.	Architects in interdisciplinary contexts: Representational practices in healthcare design	2015	Design Studies
Kleinsmann M., Valkenburg R.	Barriers and enablers for creating shared understanding in co-design projects	2008	Design Studies
Kleinsmann M., Deken F., Dong A., Lauche K.	Development of design collaboration skills	2012	Journal of Engineering Design
Kokotovich V., Dorst K.	The art of 'stepping back': Studying levels of abstraction in a diverse design team	2016	Design Studies
McDonnell J.	Collaborative negotiation in design: A study of design conversations between architect and building users	2009	About: Designing - Analysing Design Meetings
Sonnenwald D.H.	Communication roles that support collaboration during the design process	1996	Design Studies
Wang J.K., Roy S.K., Barry M., Chang R.T., Bhatt A.S.	Institutionalizing healthcare hackathons to promote diversity in collaboration in medicine	2018	BMC Medical Education
Zolin R., Hinds P.J., Fruchter R., Levitt R.E.	Interpersonal trust in cross-functional, geographically distributed work: A longitudinal study	2004	Information and organization

Notes

1. The Classification of Instructional Programs (CIP) provides a taxonomic scheme to track and report about fields of study and program completions activity. CIP was developed by the U.S. Department of Education's National Center for Education Statistics (NCES) in 1980, with the latest revision in 2020.
2. (United States Code: Support and Scholarship in Humanities and Arts; Museum Services, 20 U S C. §§ 951–968, U.S. Congress, 1988): *"music (instrumental and vocal), dance, drama, folk art, creative writing, architecture and allied fields, painting, sculpture, photography, graphic and craft arts, industrial design, costume and fashion design, motion pictures, television, radio, film, video, tape and sound recording, the arts related to the presentation, performance, execution, and exhibition of such major art forms, all those traditional arts practised by the diverse peoples of this country. (sic) and the study and application of the arts to the human environment …"*

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