Review article

The impacts of digital design platforms on design cognition during remote collaboration: A systematic review of protocol studies

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ABSTRACT

For over a decade, technology has been available to support design teams to operate in diverse physical locations and time zones. Despite this, until relatively recently designers have largely continued to work in physically co-located teams. This has all, however, changed in the last year, with designers in many countries being forced to work remotely. The problem addressed in this article is the lack of synthesised knowledge about the impacts of digital modalities on designers’ cognitive operations when they are working in distributed teams. With an emphasis on synthesis of existing knowledge, this article conducts a systematic review of research in accordance with the PRISMA framework. The systematic review identifies ten studies that have a common concern (design cognition), a common method (protocol analysis) and a common setting (collaborative yet remote interactions). This article analyses the past research, developing a collective model of cognitive operations in remote design collaboration and synthesising the findings about the impacts of technology (the platforms supporting remote collaboration) on cognition. Through this process multiple gaps in the body of knowledge are also identified, several weaknesses are uncovered and advice for future researchers is developed.

1. Introduction

Traditionally, design teams have been co-located, physically sharing the same spaces, tools, systems and platforms. Over the last few decades however, advances in information and communication technology (ICT) have expanded the conventional scope of the design workplace to encompass a range of dynamic digital environments that operate anytime and anywhere. State-of-the-art computer supported collaborative workplaces (CSCW), or computer supported collaborative design (CSCD) platforms, enable remote, typically online design processes. CSCW and CSCD have already been adopted in design practice and education, and they have attracted strong interest from research communities focused on computer-aid design (CAD) (Lahti et al., 2004; Shen et al., 2008). Furthermore, traditional social approaches to design, such as ‘co-design’ and ‘participatory design’, are also examining the benefits of interactive and collective platforms using virtual reality (VR), collective intelligence, artificial intelligence, mobile computing and social network services (Chowdhury and Schnabel, 2020; Kim et al., 2020; Lee et al., 2020). Given this growth in interest, it is not surprising that recent research on design collaboration has considered digital modalities (Idi and Khaidzir, 2018) and found that digital environments support four critical collaborative design activities: representing, analysing, reviewing and decision-making (Boudhraa et al., 2021; Chowdhury and Schnabel, 2020; Koutsabasis et al., 2012; Lee et al., 2020).

Despite these examples of interest in remote design teamwork, design cognition in teams working without contact (‘untact’) remains a significant gap in our knowledge. Furthermore, the combination of untact and diverse design teams poses a cognitive challenge for designers and some of the few studies that do exist of remote design teams seek to replicate face-to-face design approaches, even though traditional sketch activities and gestures do not work in the same way (Huang et al., 2019). Such examples suggest that cognitive activities in remote design teams differ from those in traditional co-located, concurrent design teams, but it isn’t clear how or why this is the case. To usefully understand these early cognitive studies about remote design teams, and compare their findings, a common empirical and methodological foundation is required.

Standard empirical methods for examining design cognition typically include interviews, observation studies, experiments, simulations, and reflective processes (Cross, 2011). For example, empirical studies of collaborative sketching and modelling activities in remote design collaboration rely on observations, experiments, and interviews (Eris et al., 2014; Tang et al., 2011). Interactive studies examining remote
collaboration tend to have a focus on data capture, giving them heightened interest for many researchers because their findings can be tested or validated. Such approaches tend to rely on data capturing of design media (text, audio, or video), designer interactions, and physical/virtual hybrid activities (Cheng, 2003). Underpinning several of these methods is an approach called ‘protocol analysis’, which is one of the most well-respected and rigorous empirical methods used for researching design cognition (Coley et al., 2007; Hay et al., 2017; Lee et al., 2020). This method can be used to rigorously examine both cognitive activities and design communication in teamwork. However, despite the potential of protocol analysis, past examples of cognitive research into remote design collaboration remain limited in number and often lack connections to other studies with similar contexts. As such, there is a growing need for empirical research on this topic. In response to this knowledge gap, this article uses a systematic review to develop a collective definition of cognitive operations in remote design collaboration and then examine the cognitive impact of digital modalities on remote teams.

A systematic review method is used for identifying and appraising relevant studies and evidence, and then synthesising the results of individual studies to develop deeper insights (Higgins et al., 2019). In this way, it helps researchers approach a new or growing area more efficiently, to rapidly appraise materials and through this develop appropriate research questions and frameworks. Systematic reviews adopt the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) concept to provide a rigorous, reproducible result that can be used to identify, select, appraise, and synthesise studies (Moher et al., 2009). PRISMA has been extended and refined over time to include additional selection and screening processes and an expanded checklist (Page et al., 2021). In principle, PRISMA is a staged systematic data collection process with either a four-phase (identification, screening, eligibility and included) or a three-phase (identification, screening and included) process for reporting results. The present article adopts PRISMA to formalise the systematic review of different types of cognitive evidence about design collaboration and to produce new integrated findings and analysis.

As the first stage of a systematic review defines research questions, the following section identifies four questions in accordance with the “PICO” framework (problem or population, intervention, comparison, and outcome) (Pollack and Berge, 2017; Richardson et al., 1995) and “CIOMO” logic (context, intervention, mechanism, and outcome) (Denyer and Tranfield, 2009). The methodology section then describes data selection and collection processes as well as synthesis methods. Thereafter, this article reports the synthesised results of selected protocol studies and discusses the interpretation and implications of the results. Finally, the article concludes with a discussion about limitations and contributions.

2. Background

2.1. What is the problem?

The ‘problem’ addressed in this article is the lack of synthesised knowledge about the impacts of digital modalities on designers’ cognitive operations in distributed, collaborative design processes. A wide range of professionals have already decided to transition fully or partly to remote working for the foreseeable future. Furthermore, in response to the recent COVID-19 pandemic, design practice and education have been forced to sustain successful collaboration without any physical contact between designers in different locations. Even though this change is already occurring, the cognitive impacts on design are not clear. For example, we know that this mode of creative interaction has inherently reduced communication cues and typically relies on more limited representations (e.g., instant sketches and models are more difficult to produce), but we do not know if this inhibits, or potentially improves aspects of the design process. Certainly, we could develop this knowledge by examining designers’ cognition, communication and interaction when using digital tools (Gu et al., 2011) and a small number of protocol studies on collaborative design using remote digital platforms have examined and explored selected aspects of cognitive advantage and disadvantage (Gu et al., 2011; Kim et al., 2020; Tang et al., 2011). Through a systematic review the present article addresses this problem.

2.2. What is the common context?

While it may be obvious, it is worth clarifying that the common feature in remote collaborative design is a shared digital interface, environment or platform that enables communication and interaction. Past research has identified a wide range of emerging technologies with the potential to advance remote design collaboration. Some examples are web-based collaborative design systems, VR, augmented reality (AR), and mixed reality (MR), mobile and cloud computing, and even agent-based systems. Researchers have argued that AR can be a powerful mechanism for co-creation and engagement (Cascini et al., 2020) and that networked VR-based environments can facilitate interaction between team members in distributed workspaces (Germani et al., 2012). Collectively encapsulated in CSWC or CSCD platforms, a range of commercial software systems (the most common of which are advanced forms of CAD and BIM) provide integrated support for design teams by way of shared digital workplaces for effective collaboration and communication. Both prototype and commercially available interactive digital platforms for remote teamwork are within the scope of this review, although the former dominates the research.

2.3. What comparisons and mechanisms of interest are significant?

Cognitive research in design is often conducted using a comparative structure, because absolute values are not available. For example, some common cognitive comparisons are novice vs expert designers, manual (pen-and-paper, sketch) vs digital (or CAD) tools, and conventional CAD vs emerging CAD (parametric or BIM) applications. Distributed design team processes can further consider the difference between synchronous and asynchronous actions (Rahman et al., 2013), and co-located or distributed environments (Eris et al., 2014; Gül and Maher, 2009; Tang et al., 2011). Furthermore, using protocol analysis a specific cognitive process or pattern developed from a group of participants can be compared with the results of other groups undertaking the same experiment to identify similarities or differences in cognitive operations and thereby propose new, or examine existing theories about human cognitive behaviours. Such studies emphasise the importance of both functional and behavioural comparisons, and for this reason both are included in the scope of this systematic review.

2.4. What are the relevant outcomes?

Although the main problem addressed in this article is concerned with the impacts of digital modalities in remote teamwork, the results of protocol studies can reveal many further aspects of cognitive operations. There is, however, no single desired effect of remote design collaboration, but a diverse and inspiring range of cognitive impacts arising from digital design platforms has been theorised and could be expected to be identified in this article.

3. Methodology

This article follows Pollock’s and Berge’s (2017) framework for a systematic review. This consists of six key stages: (i) clarifying aims and objects, (ii) finding relevant research, (iii) collecting data, (iv) assessing quality of study, (v) synthesising evidence, (vi) interpreting findings. The first of these stages is described previously in the article, and the present section explains the literature selection, data collection and synthesis processes. This methodology follows the PRISMA 2020 standard which highlights four methodological components in a systematic review:
eligibility criteria, information sources, risk of bias and synthesis of results (Page et al., 2021).

3.1. Finding relevant studies

3.1.1. Eligibility criteria

Summarising the research issues identified in the background section, this review uses selection criteria developed to address the following research question, “What are the impacts of digital design platforms on designers’ cognitive operations in distributed, collaborative design processes?” In accordance with the PICO framework, the key parameters of the selection criteria are defined as follows. First, this review is focused on design cognition in remote design collaboration (P, problem). Second it encompasses research articles that examine digital design platforms (I, intervention), excluding articles on co-located teamwork with no links to, or discussions about online collaboration. Third, the systematic review addresses a distinct set of methods, experimental controls, and comparators (C, comparison). Last, this review selects articles describing the impacts of digital platforms on design cognition in remote teamwork (O, outcome).

3.1.2. Information sources

Nine academic databases – Science Direct, Taylor & Francis Online, SAGE Journals, MDPI, Web of Science, JSTOR, Wiley Online Library, Cambridge Core, and Emerald Insight – were used to identify relevant research publications between 30 July 2021 and 19 August 2021. These databases encapsulate the majority of refereed journals in design domains such as Design Studies, CoDesign, Journal of Engineering Design, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, and Design Science. That is, the identification process included an acceptable range of design journals. To effectively gather the literature, the authors developed a search string, using major keywords from the research question, along with alternative words, supported by Boolean “AND” and “OR” operators. The search string is:

\[(\text{“protocol analysis” OR “protocol study”}) \text{ AND (”design collaboration” OR “design teamwork”}) \text{ AND (online OR virtual OR remote OR distributed OR digital)}\]

Initially, using a simple combination of “protocol analysis” AND “design collaboration”, produced 5773 records from the nine databases. Systematic reviews frequently start by identifying a huge number of search results that include a lot of irrelevant data, making screening by titles and abstracts also unfeasible (Bower et al., 2019; Casakin and Wodehouse, 2021; Hay et al., 2017). The solution is to refine the Boolean strings to focus the outputs into a more manageable and relevant set. For the present article, the literature was limited to research articles published in refereed journals (that is, excluding conference papers, book chapters and review articles) which also serves to limit duplication of data (with conference papers sometimes evolving into journal articles).

3.1.3. Selection process

As shown in Figure 1, from the “identification”, through the “screening” to the “included” phases, three decision points determined whether to include or exclude literature. Firstly, the identification phase selected only research articles and excluded duplicate records and inappropriate formats of publications. In the screening phase, 48 articles were screened by title and abstract using the PICO framework. 18 articles met eligibility criteria in the title and abstract. Lastly, the authors assessed the quality of the pre-selected articles for eligibility as an independent full-text review using a checklist that consisted of five questions based on the PICO criteria.

1. Does the article study remote (or online, virtual, digital, distributed) design collaboration?
2. Does the article describe a study which uses protocol analysis?
3. Does the article conduct or lead to a comparative study?
4. Does the article conduct cognitive coding results?
5. Does the research reveal any impacts of remote design collaboration on design cognition?

A simple rating system (Yes = 1; No = 0; partially = 0.5) was used by all authors for the independent full-text screening. Ten articles, which scored greater than or equal to 3.5 points by each assessor, were selected with a full consensus. For example, five articles conducting design experiments in co-located environments were included because they received full points for the second, third and fourth questions, while they only received 1 or 0.5 points for the last question. In contrast, this last screening process excluded three articles that re-used protocol data already published by the same authors. In addition, although the initial search focused on “protocol analysis” OR “protocol study”, three articles didn’t conduct conventional design experiments using protocol analysis, but instead used alternative methods such as qualitative content analysis (Lahti et al., 2004), dialogue analysis (Koutsabasis et al., 2012) and a video ethnographic approach (Christensen and Abildgaard, 2018). Two articles which scored less than 3.5 points were also excluded because they didn’t conduct remote design experiments and a comparative study. At the end of this process of identification, screening, and inclusion, 10 articles were identified which directly address the research question and the scope of the systematic review in this article.

3.2. Risk of bias

A systematic review typically assesses risk of bias in the final set of studies, including selection, detection, and attrition biases (Page et al., 2021; Pollock and Berge, 2017). The Cochrane risk of bias tool is used for this purpose (Higgins and Green, 2008). From this perspective, the key risk in protocol analysis in the design domain is ensuring coding reliability. In addition, Rahimian and Ibrahim (2011) highlight the critical importance of the validity of the experimental procedure. Thus, this systematic review examines both reliability and validity in terms of risk of experimental bias. A review of the final set of ten journal articles does not reveal any which are excluded for risk of bias, in terms of either reliability or validity.

3.3. Synthesis of results

Protocol studies produce not only quantitative results, but also in-depth qualitative discussions. As such, the method used for synthesising their results needs to consider both quantitative and qualitative data. The quantitative data analysis can adopt a meta-analysis or statistical approach (Page et al., 2021; Pollock and Berge, 2017). For example, the general characteristics and coding results of protocol studies can be reported using quantitative synthesis. However, cognitive studies tend to use their own coding schemes. That is, there is no unilateral consensus about coding variables or categories. Thus, the quantitative synthesis in the present review is limited to general characteristics of the research such, as participants and experimental settings. After describing these characteristics, the intervention and comparison variables are synthesised in this review.

Data synthesis can include a qualitative summary of results, although this is not recommended in all fields of research (Pollock and Berge, 2017). Nevertheless, given the variety of coding results developed in protocol studies in design, a qualitative synthesis is acceptable (Hay et al., 2017). For example, there are some differences in the use of cognitive models and corresponding terminologies. The qualitative synthesis starts with the identification of cognitive models and coding schemes, which can also provide a holistic view of the outcomes. The present review then categorises the findings of the articles in terms of their cognitive models and then discusses key communicative and collaborative impacts of digital design platforms.
4. Results

The final set of ten research articles (A1-A10) examined in this review was published between 2004 and 2021. Four articles were published in Design Studies and two in CoDesign. Both journals have regularly published protocol studies on individual design processes and collaborative processes. Four articles have a focus on ‘architectural design’ (Gül and Maher, 2009; Kim et al., 2020; Kim and Maher, 2008; Rahimian and Ibrahim, 2011), three address ‘industrial design’ (Boudhraa et al., 2021; Dorta, 2008; Tang et al., 2011), two ‘engineering design’ (Eris et al., 2014; Wu and Duffy, 2004) and one investigates participatory ‘urban design’ (Chowdhury and Schnabel, 2020).

4.1. General characteristics

4.1.1. Participants

Since design experiments for protocol analysis are typically conducted in controlled laboratory contexts, experimental settings are the first important methodological mechanism. Defining participants is one common component of the “PICO” framework, population, but considering specific age, gender or background tends not to be a core concerned

in these design studies. Participants in design experiments are usually selected for a comparative purpose (e.g., different skills or experiences) or just a defined group of people (e.g., Master’s students, Graduate Designers).

74 teams and 161 participants took part in the ten studies (see Table 1). Eight studies involved only student participants, with or without experience in the given digital tools, because they could learn the new digital interfaces in pre-experimental sessions. In contrast, A4 recruited architects to investigate professionals’ design representations and A8 recruited laypeople for a participatory design experiment. This suggests that cognitive research in professional teamwork is largely a gap in present research and it is potentially a valuable area for future research (Kim et al., 2020).

Only one team participated in studies A1 and A4, while the maximum number of teams was 20 in A2. The average number of teams was 7.4 (SD = 6.13) across all studies. In six studies (A2 to A7), all teams were formed by a pair of participants, while the maximum number of participants in a team was four in A1, A8 and A9. While “pairs” might be the optimal team for a laboratory study, knowing the typical number of team members in design education and practice would seem to be a necessity for future research in this area.

Figure 1. A three-phase selection flow based on the PRISMA flow diagram templates (Moher et al., 2009; Page et al., 2021).
4.1.2. Experimental settings

As shown in Table 1, this review identified 15 design tasks across four design domains – 9 architectural design, 3 industrial design, 2 engineering design, and 1 urban design. To compare different digital tools, participants in A4, A5 and A7 conducted between two and four consecutive design experiments using provided design tasks that were equivalent to each other in scale and complexity. Between 20 min and 1 h were given for each design session in a typical laboratory setting, while A8 didn’t clearly state session time. In addition, A9 investigated five weeks of communications over social network service (SNS) platforms. Nonetheless, a widely accepted session time for a teamwork experiment was 30 min, which was adopted in five studies (A4 to A7, A10). From these five it is apparent that even this short timeframe produced a large volume of detailed data for protocol analysis. However, a short experiment time combined with a small sample size might be an on-going limitation in research of this type (Lee et al., 2015).

Since verbal communication naturally occurs during collaborative design, all studies except for A9 used concurrent verbalisation (CV) to develop protocol data. A9 didn’t use conventional verbalisation methods, but instead, textual, graphical communications on SNS platforms provided a type of concurrent expression or utterance. The quality of CV is usually enhanced by visual cues on video recordings or a post-experiment interview or “retrospective verbalisation” (Lee et al., 2015). As such, A1 used interviews to check encoded data and A4 conducted a retrospective coding process. In contrast, A7 used video interaction analysis that was supported by graphical, textual, and verbal communication, because the research focus was on multimodal communication, like gesturing. A3 captured gestures using video, treating physical gesturing as a communication tool and A4 also used video recordings to determine representation and collaboration modes. In addition to CV, A2 and A10 employed self-reporting using Design Flow graphs to capture participants’ mental states.

Typically, in these studies participants were asked to conduct a given design task using manual and/or digital tools, and they were also led to develop certain types of design representations that assisted encoding of the collected verbalisations. Interestingly, seven studies asked participants to sketch, five (A2, A5 to A7, A10) of which highlighted digital sketching tools. In contrast, 3D modelling was used for design representation in teamwork in VR or AR environments (A2 to A4, A8). Whilst design communication involved various types of representations (Lee et al., 2020), sketching and modelling were dominantly investigated for remote design collaboration because both are useful for investigating, exploratory, iterative design processes (Hay et al., 2017).

4.1.3. Arbitration and intercoder reliability

Of the ten papers, a high proportion did not describe intercoder reliability or arbitration processes to a standard that might be acceptable in rigorous research practice. Seven papers (A2, A3, A6 to A10) described using two coders for protocol data, but only one (A7) presented kappa values for intercoder reliability. However, A1 adopted interviews to justify the encoded data and A2 used participants’ rates and questionnaires to provide an additional level of validity. Furthermore, A4 used the Delphi method and A5 separately addressed procedural validity and reliability. These approaches might provide partial alternatives to reporting intercoder reliability, but the reliability would be ensured by using Holsti’s coefficient, Krippendorff’s alpha and Cohen’s kappa (κ) indexes.

4.2. Interventions

Except for A10, which used Hybrid Ideation Space (HIS) as originally introduced in A2, each article introduced its own new digital design platform(s) for design teamwork. Five studies (A2, A4, A5, A8, A10) focused on VR collaborative tools and two (A6, A7) dealt with advanced CAD tools. A3 introduced an AR platform enabling a tangible user interface (TUI) and A9 adopted SNS platforms for collective design collaboration. Interestingly, VR and CAD tools dominated the studies of sketching functions (A2, A4, A5, A6, A7, A10). Although emerging ITC technologies have enabled new “digital design” paradigms (Lee et al., 2020; Oxman, 2006), many collaborative platforms have still tried to emulate the traditional pen-and-paper or physical working environments (A2, A4, A6, A7). This trend may be caused by the flexible and intuitive nature of sketching activities, which is often linked to design creativity (Bilda and Demirkan, 2003; Lee et al., 2015; Verstijnen et al., 1998) or multimodal communication in co-located design environments (Chris-tensen and Abildgaard, 2018; Eris et al., 2014).
While the traditional or digital sketch tools could have some advantages over conventional CAD platforms, sketching has some clear deficiencies for communicating complex designs (A5) and supporting co-located design processes which have been relocated to online platforms. Thus, easy and shared representation of design (A8) and collective and heterogeneous interactions (A9), enabling both synchronous and asynchronous collaboration, should be further elaborated in terms of social creativity (Lee et al., 2013). In summary, findings begin to suggest that cognitive activities in digital design platforms could differ from those in “traditional” (pen-and-paper) environments. Beyond the traditional co-located, face-to-face version of teamwork, the digital design platforms would better support remote, immersive, and shared interactions and collectiveness in designing.

4.3. Comparison

Seven of the collected articles hypothesised that there might be different cognition processes and types of collaboration in different design platforms. In particular, six (A2 to A7) compared traditional designing to design collaboration using emerging CSCD tools. For example, A2 compared physical modelling activities to three types of design ideations (hybrid model, immersive model making, and immersive sketching) using HIS and Hybrid Modelling (HM). A3 also compared a “traditional” graphic user interface (GUI) to a TUI in terms of spatial cognition. As mentioned before, sketching is one of the most popular themes in design cognition research. As such, A5 and A6 compared manual sketching to 3D and digital sketching tools, respectively. Furthermore, A4 compared co-located sketching to sketching in three digital environments (remote sketching, 3D VR world, 3D VR world with sketching). A7 also investigated co-located and distributed environments. Lastly, A9 compared three different SNS applications to explore remote, collaborative ideation. In contrast, three articles (A1, A9, A10) addressed specific cognitive patterns in teamwork without any clear comparator (control) groups. For example, A1 compared teleological, rational, and epistemic links between team design and collective learning, while A10 examined co-ideation processes such as collaborative conversation, collaborative ideation loops and collaborative moving. A8 compared the cognitive activities of eight design sessions in terms of design collaboration and communication. Thus, these three articles implicitly discussed the impacts of digital design platforms in remote teamwork, compared to the seven studies that had at least one comparator in the experiments.

Expert panel assessment or consensus assessment technique (CAT) is often used in a protocol study to further compare the cognitive characteristics or allocations with the final design results (Lee et al., 2020). As such, it is not surprising that two articles conducted expert assessments of participants’ design deliverables. A6 used seven criteria for the evaluation (design concept, functionality, material utility, scenario, innovation, style and form, completeness) and the design results using a traditional sketching environment received a slightly higher average score than those using a digital sketching tool. A8 also conducted expert evaluation using three criteria (functionality, aesthetics, and experiential qualities) to identify ideal VR-enabled collaboration and collaboration patterns. Alternatively, participants’ ratings using Design Flow graphs (A2 and A10) and questionnaires (A2 and A9) were also used as an additional layer of information for three comparative studies.

4.4. Cognitive models and coding schemes

All protocol studies in design explicitly or implicitly adopt cognitive models and develop relevant coding schemes to capture participants’ cognitive characteristics during design. Since the main problem addressed in this strategic review is concerned with the impacts of digital modalities on cognitive operations in distributed, collaborative design processes, the selected articles directly address this issue. However, since design collaboration is naturally reliant on concurrent expressions or utterances, the ten studies also typically highlight cognitive properties revealed in communicative design protocols. Specifically, five articles (A2, A4, A8, A9, A10) deal with co-ideation processes, which are a dominant cognitive model. Conversely, A4 focused on designers’ interactions with design representation in virtual environments and A8 examined both design collaboration and communication. In addition, A9 specifically investigated design activity and communication levels and A7 conducted a comparative analysis of multimodal communication, with a coding scheme limited to sketching activities. That is, most of the collected articles were based on collaboration and/or communication models, even though the specific issues they are addressing vary. This observation about the cognitive models in the ten articles can be encapsulated in an interactive model of communication and collaboration (Figure 2).

As shown in Figure 2, some research on design cognition in remote teams starts by considering the interactive relationship between communication and collaboration. Design communication is central to design collaboration, particularly in a distributed environment, whether synchronous or asynchronous (Chiu, 2002; Kwan, 2000). Communication in a digital design platform is also central to the co-creation of ideation (A2, A8, A9, A10) or co-creation (A4) processes, collectiveness (A1, A8, A9, A10) and communicative interactions (A2, A9, A7, A10) that impact on collaborative activities. In contrast, digital design collaboration may require new types of spatial cognition (A3 and A5) and different or similar design activities (A5, A6, A7, A9). Digital design collaboration calls on more diverse interactions with digital media and design representation (A3, A4, A6, A8, A9) than traditional practices do, potentially leading to specific patterns in communication. The two directions of conceptual flows (communicative collaboration and collaborative communication) are limited to understanding the selected articles, because the flow from collaboration to communication can include co-ideation and collectiveness. However, the most important finding in this synthesis of cognitive models is the interactive relationship between existing communication and collaboration models.

Multiple coding schemes were developed or adopted in the collected articles. A1 developed a model of collective learning in design from the links between team design and collective learning that were identified by two levels of a coding scheme, team design activity (input knowledge, team design goal, output knowledge) and collective learning activity (input knowledge, learning goal, learning operator, learned knowledge, rationale trigger). A2 addressed cognitive states and interaction, using Design Flow (apathy, worry, anxiety, arousal, flow, control, boredom, and relaxation) as well as the NASA Task Load Index (mental, temporal, and physical demands, performance, effort, and frustration). A10 also used Design Flow along with design conversation elements (presentation and discussion) and collaborative ideation loops (proposing, negotiating, and observing). A3 developed four levels of a coding scheme (action, perception, process, and collaborative levels) to investigate spatial cognition. A3’s coding scheme was selectively adopted in A5, along with Suwa et al.’s cognitive actions (1998). Based on relevant coding schemes in the literature, A4 also developed complex, multi-levels of coding schemes – consisting of realisation action and process, agents’ actions, perceptual focus, design space, representation mode, and collaboration mode – to study representation in collaborative design.

A6 used the FBS framework to compare design processes in traditional and digital environments, while A7 developed a coding scheme of sketching activity (create, delete, gestures, verbalise, access external sketch), for multimodal design communication, to compare design in co-located and distributed environments. A8 developed a combined coding scheme of design collaboration (communication control, design communication, social communication, communication technology) and design communication (design concept, design detail, design task). A9 also used two levels of a coding scheme, design activity level (information sharing and problem exploration) and communication level (interaction and engagement). Schön’s model (framing, moving and reflecting) was also used for the identification of problem exploration in A9.
In summary, since protocol studies in this systematic review addressed both communication and collaboration, the chosen coding schemes tended to include communication and collaboration levels of codes and then specify design activities such as interactive and collective activities. Gero’s, Schön’s, and Suwa et al.’s coding schemes were also used to identify general characteristics of design process and content. Because of the complex nature of design collaboration, multidimensional coding schemes were developed to compare different aspects of the data. Nonetheless, the following sections synthesise the results of the articles, classified using the interactive communication and collaboration model in Figure 2.

4.5. From communication to collaboration – communicative collaboration

4.5.1. Co-ideation

In the same way that traditional design modes can support ideation, so too can a virtual digital platform (HIS), delivering sufficient information, communication and feedback, providing a simple and intuitive interface is available to support immersion and presence (A2 and A10). These findings are echoed in the other virtual environment studies that enabled effective transmission of information, design conversation and shared activities (A4 and A8). Furthermore, social networking could be useful to share design ideas and information, supporting problem framing and ideation in design collaboration (A9).

4.5.2. Collectiveness

In terms of collective learning, computational agents with learning capability can be developed to enable knowledge input, knowledge acquisition and transformation, knowledge storage and retrieval, and learning triggers. The collective learning can result in mutual knowledge evolution and the generation of common knowledge (A1). A virtual environment also supported collective design imagination and representation (A8) and a SNS acts can act as a collective medium for information sharing and discussion (A9). Finally, the virtual co-ideation tool also enabled real-time collective ideation as well as collective dynamics, promoting active participation (A2 and A10).

4.5.3. Interaction

A10 highlights social interaction that might be improved by the collective ideation process of a digital platform. A4 also examined designers’ shared activities in a virtual environment. Furthermore, online interaction, sharing information and gaining feedback on design ideas, virtually or remotely, could impact on a designer’s problem exploration and communication (A9), multimodal communication (A7) and ideation (A2 and A10). In summary, interaction in communicative collaboration tended to capture the changes of design communication happening in both synchronous and asynchronous environments. In contrast, in distributed environments they were more focused on collective communication between team members.

4.6. From collaboration to communication – collaborative communication

4.6.1. Spatial cognition

A3 found that TUIs impacted on designers’ perceptions of ‘spatial relationships’ (Z = -1.964, p = .05), which might lead to creative design. A5 also revealed that a 3D sketching interface (a 6DOF haptic device) could improve designers’ perception of visuo-spatial features, impacting on collaborative activities including cognitive synchronisation actions (Z = -5.555, p < .001), related to problem finding and problem solving. Unlike the virtual tools (A4 and A8), both tangible, digital tools in the real world could facilitate unexpected discoveries as well as the development of the problem space.

4.6.2. Design activity

Interestingly, A6 found that there were no significant differences between co-located and distributed design processes in terms of the FBS framework (x² = 5.99, df = 2, p > .05), while A7 revealed that the structure of sketching activities were different in the two settings in terms of multimodal communication (a significant interaction effect between conditions and activity duration, F(1,9) = 18.7, p < 0.05). Specifically, designers in the distributed environment were forced to more frequently use graphical, textual, and verbal communication, because remote design teamwork has inherently reduced visual cues and relies on the limited representations. In short, the higher-level cognitive activities might not be impacted by the change of design platforms, but the micro-level activities could be. Furthermore, A5, using Suwa et al.’s coding scheme (1998), precisely described the impacts of a 3D sketching interface. The digital haptic tool could impact on the quality of physical-actions (e.g., a faster production of design elements) (x² = 12.851, df = 1, p < .001), the occurrence of perceptual-actions that might be related to unexpected discoveries (x² = 9.889, df = 1, p < .01) and the occurrence of functional-conceptual-actions that could be regarded as co-evolutionary actions (x² < 53.555, df = 1, p < .001). Lastly, A9 identified that the different collaborative settings of SNSs developed different design activities in terms of information sharing (information types and sources) and problem exploration activities (framing, moving, and reflecting).

4.6.3. Interaction

Interaction in collaborative communication addresses designers’ interactions with digital media and representations, which are closely related to Oxman’s (2006) last three classes of interaction. A3 argued that a TUI could facilitate designers’ interactions with a design model, so-called “reflective interaction”, (e.g., more ‘movement’ modelling actions, Z = -51.964, p = .05), potentially suggesting creative leaps in design. Furthermore, ‘Design’ and ‘Touch’ gestures could be interpreted as immersive gestures, assisting designers’ cognition. A4 discovered that there was a difference in designers’ interaction with design representations between face-to-face sketching and 3D modelling in virtual environments, particularly, realisation actions and collaboration modes, and thus a cognitive impact of collaborative virtual environments. A8
suggested the affordance of technology could develop active and interpretative interaction, along with the easy nature of design creation, facilitating participatory design. A9 also highlighted that the affordances of SNSs could impact on interaction and engagement in the communication level, in terms of asynchronous and synchronous interactions.

5. Discussions

agents, enables mutual knowledge evolution and the generation of substantial knowledge. Furthermore, the macro version of digital modalities and processes can be regarded as a digital ecosystem based on interactive and collective platforms (Lee et al., 2020). Key functionalities of interactive and collective platforms can be classified using the ‘5WH’ genome framework of collective intelligence (Malone et al., 2010) or computational entities such as user, content, location and time. For example, user-based functionality can include extrinsic hierarchy, extrinsic crowd, intrinsic hierarchy and intrinsic crowd, while content-based functionality considers collaborative creation and decision, collective creation and decision, and opportunistic creation and decision. The spatio-temporal functionality deals with the ability to work anywhere (local or global) and anytime (asynchronous or synchronous) (Lee et al., 2020). In this way, the collective and heterogeneous interaction of a design platform mediates socially extended cognition in remote design collaboration.

5.7. Summary of the outcomes

In addition to the synthesis of the research outcomes by the communication and collaboration models, this review further summarises the outcome of each article with a focus on the impact of digital design platforms on design cognition in remote collaboration. Six articles identified the cognitive impacts of remote collaborative platforms as follows.

- There is an impact on designers’ shared activities, creating external design representations that depend on the diverse interfaces of digital tools (A4), and multimodal design communication (increased use of graphical, textual, and verbal communication) and the structure of sketching activity (A7). In spite of this, there is no significant difference in the higher-level cognitive activities between co-located and distributed collaboration (A6).
- Participatory design activities relying on communication, presence, and co-presence, along with the easy generation of 3D artefacts, are impacted (A8).
- There is an impact on collective information sharing and discussion, particularly supported by SNSs, and problem framing and ideation (A9), and social interactions and collaborative ideation in terms of design learning (A10).

In addition, emerging digital modalities in co-located environments, supporting multimodal interactions, have suggested the following implications for design cognition or activities in remote design collaboration.

- An intuitive digital tool like HIS, enabling both traditional sketching and virtual modelling with a physical model, can support ideation as well as communication and feedback (A2).
- Tangible user interface (TUIs) impacts on spatial cognition (A3) and a tangible, haptic design interface (3D sketching interface) can improve problem-finding behaviours and coevolutionary conceptions of perceptions (A5).

Lastly, design experiments using traditional sketching tools demonstrated that collective learning, potentially supported by computational agents, enables mutual knowledge evolution and the generation of common knowledge (A1).

5. Discussions

This systematic review has identified six cognitive issues – co-ideation, collectiveness, interaction (communicative), spatial cognition, design activity, and interaction (collaborative) – in terms of the impacts of digital design platforms on remote design collaboration. These issues were closely related to existing communication and collaboration models. Nevertheless, team coordination, managing and developing a team cognition or mental model (Badke-Schaub et al., 2007), or at least the coordination of design information and tasks (Chiu, 2002), should be important issues in a distributed design environment, as they could impact on both communication and collaboration activities. Thus, team cognition models should be rigorously tested in this domain. In addition, due to a limited number of articles that fulfilled the search conditions, there might be other important issues that are not directly identified in this systematic review. Beyond the six cognitive issues, this section discusses three additional research factors in remote design collaboration, (i) collective design collaboration, (ii) team creativity, and (iii) productivity.

5.1. Collective design collaboration

Co-ideation in this review has been limited to information sharing and problem exploration using intuitive design media. Collectivity issues have focused on collective knowledge, information or interaction, captured in the design communication and ideation process. However, co-ideation can also be investigated as part of co-creation or co-design that is largely related to interactive and collective aspects of design collaboration (Lee et al., 2020) or even “collective design” (Ozkil, 2017). Furthermore, the macro version of digital modalities and processes can be regarded as a digital ecosystem based on interactive and collective platforms (Lee et al., 2020). Key functionalities of interactive and collective platforms can be classified using the ‘5WH’ genome framework of collective intelligence (Malone et al., 2010) or computational entities such as user, content, location and time. For example, user-based functionality can include extrinsic hierarchy, extrinsic crowd, intrinsic hierarchy and intrinsic crowd, while content-based functionality considers collaborative creation and decision, collective creation and decision, and opportunistic creation and decision. The spatio-temporal functionality deals with the ability to work anywhere (local or global) and anytime (asynchronous or synchronous) (Lee et al., 2020). In this way, the collective and heterogeneous interaction of a design platform mediates socially extended cognition in remote design collaboration.

Compared to expert design teams, a team of novice designers could develop less connections to key ideas and concepts (Crismond, 2001) and less effective cognitive processes and conversation activities (Kiernan et al., 2020). Novice designers also produce different problem decomposition and recomposition strategies from those of engineering design experts (Song and Becker, 2014). Comparing individual novice and expert design activities is a recurring topic in the field of design cognition (Lee et al., 2015) and further research on collective design collaboration should consider these different levels of expertise in a collaborative context.

Despite all of the new observations and critical comparisons offered in this article, the implications of the synthesised results in this review might be limited to a better understanding of real-time remote collaboration, because only A9 discussed team cognition in both asynchronous and synchronous design teamwork. However, general design practices across spaces are largely supported by asynchronous activities and tools. Specifically, design teams distributed in different countries could further examine the significance of non-real-time collaboration. Focusing on an ‘any-time’ collaborative platform (Fan et al., 2012; Lee et al., 2020), a comparative study on synchronous and asynchronous communications in remote teamwork should be a promising future direction for researchers.

5.2. Team creativity

This review has revealed that intuitive and tangible digital media could develop unexpected discoveries and co-evolutionary actions that might support creativity. Furthermore, co-creation and collective design could, substantially, lead to creative activity and cognition in social design space (Giaccardi, 2004), because the relationship between team members’ operations can be linked to “social creativity” (Fischer et al., 2005) or “group creativity” (Snader and Jin, 2016). “Mobile creativity” is also more related to social creativity than individual creativity (Lee et al., 2013). Furthermore, a “co-evolutionary” process could not only occur in between various design, representation or collaboration modes, but also appear in distributed and shared design spaces and design strategies. The impact of remote design collaboration on team creativity is still, however, largely undiscovered territory, although there are a small number of interesting studies in this field.

D’Souza and Dastmalchi (2016), for example, address small creative events in a multidisciplinary design team that are potentially connected
to big creative leaps. Their micro and macro levels of protocol analysis reveal that team members’ background knowledge level impacts on creative events. Design team’s thinking and reasoning style could also impact on the degree of novelty of the design outcome that is measured by the SAPPHiRE (State-Action-Part-Phenomenon-Input-oRgan-Effect) model of causality (Mulet et al., 2016). On the other hand, mass interaction using collective design, could also result in creativity (Phare et al., 2018). As such, collective and artificial intelligence can be regarded as a creative collaborator beyond human collaboration. Interactions with avatars in virtual worlds is another example in this regard, overcoming “remoteness” and providing a sense of shared virtual presence (Gu et al., 2011).

5.3. Productivity

The recent practice of forming diverse design teams in distributed environments poses a significant challenge for assuring the productivity for designers, but, interestingly, the collected articles identified in this systematic review rarely mention this. For this reason, there is a need to apply methods for measuring the effectiveness and efficiency of teamwork (Goldschmidt, 1995) along with those related to interpreting linkograph data (Cai et al., 2010; Kan and Gero, 2008). In essence, past research suggests that generating ideas and defining problems at a system level positively impacts on productivity in a team (Costa and Sobek, 2004), while design productivity might be enhanced by various ideation methods (Cai et al., 2010; Goucher-Lambert and Cagan, 2019). Thus, productivity can, and should be investigated in the co-ideation process.

Remote and synchronous collaborative design tools range from interactive tangible devices to internet-based applications, such as videoconferencing and instant messaging, addressing human–human interaction and teamwork-related behaviours (Germani et al., 2012). Interestingly, although a videoconferencing tool (e.g., Microsoft Teams, Zoom, Google Meet, and Skype) is the most accessible, widely used, approach to remote collaboration, there is little research on this essential design environment. These online meeting platforms use similar visual cues and communication approaches to mimic meeting in a co-located environment, but they are fundamentally not the same. Thus, videoconferencing tools as platforms for design interaction could also be considered in terms of productivity and efficiency of remote collaboration.

6. Conclusion

This article has conducted the first systematic review of cognitive studies on remote design collaboration, formulating research questions and frameworks for empirical research on this topic, as well as providing a holistic understanding of the impacts of digital design platforms on design cognition. In response to the recent COVID-19 pandemic, design practice has been forced to sustain successful collaboration without any physical contact between designers in different locations. This remote or hybrid teamwork has become the “new normal” in many countries, but interactive and collective cognitions in remote teams are still not well understood. The development of new knowledge to support improved remote design teamwork has required the development of a significant body of empirical research, for which this review provides a systematic view. The synthesis of the outcomes of the identified articles reveals that digital media in distributed environments could positively impact on co-ideation, collectiveness and spatial cognition, and develop different types of design activities and interactions (communication and collaboration). Such findings are potentially quite promising, despite the limited scale of data used to draw these conclusions.

Unlike a conventional systematic review, the review in the present article is limited to a largely qualitative summary of results, because there is no consensus on experimental settings and coding schemes. The interventions of design experiments also vary. In addition, the risk of bias was not fully addressed in this review, because of small sample sizes and some unavoidable limitations of protocol analysis. Nonetheless, applying a rigorous review process like the PICO framework at least partially compensates for these limitations.

There are several possible areas of expansion arising from this article. For example, while this article was limited to protocol studies, its scope could be extended to accommodate alternative methods such as qualitative content analysis and dialogue analysis, because they are also rigorous methods and provide quantitative data similar to protocol analysis.

Finally, from a theoretical perspective the unified view of cognitive impacts developed in this article contributes to advancing knowledge about the challenges and opportunities of remote design collaboration. In addition, in a practical sense this article provides the foundations for future empirical studies to develop research problems and methodologies that directly advance our understanding of design cognition in remote teams.

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Author contribution statement

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