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Collaboration on large interactive displays: a systematic review

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Large Interactive Displays (LIDs), such as tabletops or interactive walls, are promising innovations, which are increasingly used to support co-located collaboration. Yet the current evidence base on the impact of LID use on collaborative processes and outcomes, and associated

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influencing factors, is fragmented, particularly in comparison with other media. To address this gap, a systematic review was carried out in the databases Web of Science, Psych.Info, ACM, Elsevier, JSTOR and Springer and in the ACM CHI conference database. A corpus of 38 articles with experimental study designs met the eligibility criteria and was analyzed in-depth. With regard to collaboration processes, the findings suggest a relatively clear advantage of the use of LIDs over classic forms of collaboration, in particular over single-user environments (e.g. laptops). With attention to collaborative outcomes, positive effects of LIDs were identified for knowledge gains and social encounters, and mixed effects for task-related outcomes. The analysis further shows relevant influencing factors of LID, such as the separation of personal and joint work spaces and the deployment of horizontal instead of vertical displays. Conceptual and practice implications are discussed.

KEYWORDS *Large interactive displays, large interactive surfaces, interactive walls, interactive tabletops, collaboration theory, systematic review*

CONTENTS

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1. INTRODUCTION AND BACKGROUND

Large Interactive Displays (LIDs), such as tabletops or interactive walls, have taken on a particular role in the ever-growing field of computer-supported collaboration. They hold the promise of enabling effective co-located collaboration. One of LIDs' key features is conceived to be the integration of affordances offered by collaboration in physical space – for example the joint development of a sketch on paper – with the advantages of digital collaboration (Müller-Tomfelde, Müller-Tomfelde & Fjeld, 2010). It is this convergence that can enable more fluent collaborative interaction – for example smooth(er) transitions between individual and group work and between different types of activities (Rogers & Lindley, 2004). Positive expectations and favorable perceptions have led to the implementation of LIDs in a wide range of practice settings. For example, LIDs are used in financial institutions for customer meetings, in formal educational settings for class orchestration, and in informal learning settings such as museums for information presentation and guidance (Beheshti, Kim, Ecanow, & Horn, 2017; Nussbaumer, Matter, & Schwabe, 2012).

Despite the increased use and interest, the evidence base and the research community are fragmented across different fields, groups and strands, such as human-computer interaction, computer-supported learning, computer-supported collaborative work and educational technology, just to name a few. There is not even a commonly acknowledged notion for the technology itself, with relevant literature being published using terms such interactive display, tabletop, interactive wall, wall display, tabletop interfaces and multi-touch. In line with many of the scholarly publications on this topic (Ardito, Buono, Costabile, & Desolda, 2015; Buisine, Besacier, Aoussat, & Vernier, 2012; Mueller-Tomfelde, 2012; Müller-Tomfelde & Fjeld, 2010; Rogers & Lindley, 2004), the term "Large Interactive Display" is used in this review. The viable alternative "Large Interactive Surfaces" was put aside – inter alia because it was, unlike "interactive" and "display" not part of most common keyword terms for CHI papers on the subject "collaboration, group or team or work or education or learning or CSCL or CSCW" at the time of writing the study.

Another motivation for this systematic literature review was that research that systematically analyzes and summarizes the impact of LIDs on collaborative work is rare. Prior reviews have conceptualized LID affordances and benefits from technological and historical perspectives. (See also section 1.2). What is lacking is, however, a systematic and comparative analysis of the effects of LIDs on collaborative processes, associated outcomes, and influencing factors which impact LID-based collaboration. In our view, LID affordances can only be fully understood if compared to other, alternative tools and/or by comparing various designs.

The main motivation of developing this review was thus to address these three aspects, with the underlying rationale to "defragment" and systematize the current evidence base. To this end, we have systematically reviewed high-quality, experimental studies on LIDs published in the last twenty years, drawing on the Input-Process-Output framework that has proved valuable in the conceptualization of collaborative work (McGrath, Arrow, Gruenfeld, Hollingshead, & O'Connor, 1993; Pinsonneault & Kraemer, 1989). To contextualize our research, we will now briefly outline the conceptual foundations of LIDs and summarize the findings from prior reviews.

1.1. Conceptual foundations

Research into the development of LIDs adheres to long-held views on the supportive role that technology and external representations play in the domain of group work (Salas, Cooke, & Rosen, 2008). The rationale is that well-designed workspaces help improve collaboration processes and outcomes of group work. Concretely, LIDs help groups view, interact with and generate artifacts, such as photos, spreadsheets, plans, text, graphic representations and videos, in a concerted manner. LIDs can be conceptualized as socio-cognitive tools that shape the collaborative processes and outcomes of these processes. LID elements that impact social interaction are the round-table constellation, face-to-face situations (Buisine et al., 2012) and the availability of personal spaces (Scott, Grant, & Mandryk, 2003). Social interaction is further shaped by the availability and placement of entry points and the skillful handling of physical and digital artifacts that can spark the curiosity and interest of collaborators to co-manipulate these objects (Rogers, Lim, Hazlewood, & Marshall, 2009). For example, the particular properties of LIDs (e.g. the number of entry points) condition collaborative processes in the form of the social interaction that unfolds between group members, which manifest for example in turn-taking patterns (Schneider et al., 2012). The cognitive aspects are contingent on the properties of LIDs that allow users to offload information processing and problem-solving by externalizing information (Fiore & Wiltshire, 2016). For example, opportunities for collaboratively engaging with external representations can activate concepts in people's long-term memory and thus help them offload and stimulate cognition (Afonso Jaco, Buisine, Barré, Aoussat, & Vernier, 2013).

1.2. Findings and limitations of previous reviews

A number of reviews reflect the substantial scientific interest in LIDs during the last two decades. Previous reviews have examined LIDs mostly from a technological or historical perspective, i.e. focusing on the evolution of the state-of-the-art in technological developments. Scott et al. (2003) reviewed literature on collocated group work up until 2003 and proposed guidelines for applications supporting collaborative work using LIDs. For example, they suggest that when designing LIDs smooth transitions between individual and group work and simultaneous user actions should be supported. Similarly, Müller-Tomfelde and Fjeld (2010) reviewed fifteen years of scientific research into interactive tabletops, focusing on emerging technologies (i.e. touch input, large displays, software applications and protocol standards). They pointed to key features such as multi-touch and tangibility as well as direct-display technologies and described their impact on research and development. Reviewing 25 years of interactive tabletop research, Bellucci, Malizia, and Aedo (2014) elucidate the design space of LIDs. The authors focused on the analysis of (a) hardware technologies and (b) interaction modalities (multi-touch, tangibles, touchless). Higgins, Mercier, Burd, and Hatch (2011) examined the potentials of LIDs in classrooms as means to support learning and proposed a typology that distinguishes characteristics of surface (geometry and display type), touch (touch sensing, tangibles, styli) and connectivity (range of input and output capabilities). A recent review of 206 articles (Ardito et al., 2015) focused on the use of large displays in public or semi-public spaces and the ways in which they shape human-computer interaction. The authors concentrated on the technological characterization of LIDs and in particular on input factors, finally emerging with a classification scheme that differentiates visualization technology, display setup, interaction modality, application purpose and location.

In essence, these prior works offer important insights into the technological design of LIDs, conceptualizing the central affordances of LIDs for supporting collaboration and define interesting areas for future research. On this basis, the need increases for analyzing LIDs, too, from a psychological perspective on their effectiveness in sustaining collaborative work in comparison with other media and tools. This is the gap that the present review seeks to address.

2. APPROACH AND METHODS

2.1. Research questions and goal

The present review addresses the following research questions:

RQ1: What are the effects of LIDs on collaborative processes, particularly in comparison with classic media such as paper-based collaboration and small displays?

RQ2: What are the effects of LIDs on collaborative outcomes, particularly in comparison with classic media, such as paper-based collaboration and small displays?

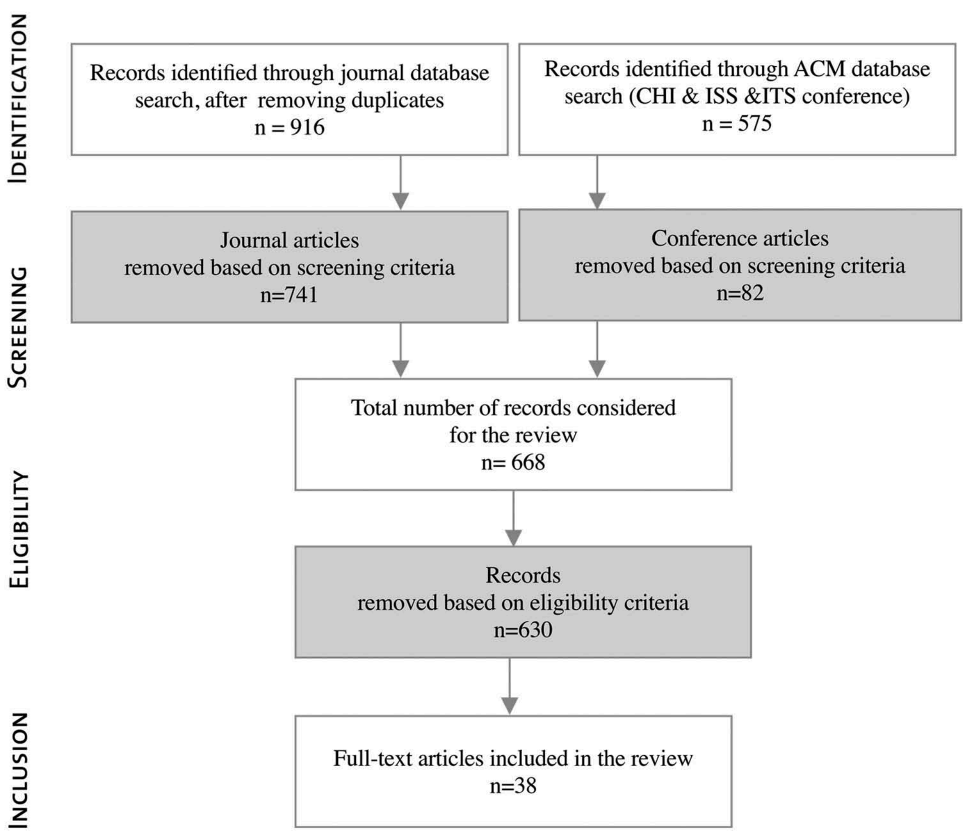
RQ3: What are the design principles and other influencing factors that impact LID-based collaboration?

The potential finding that LIDs influence collaboration processes and trigger positive outcomes attendant to these processes is not only of scientific interest, but has practical implications, too, when compared with other (less-future-oriented and more familiar) media settings for groups. Accordingly, we added paper-based and single-user environments such as Personal Computers (PCs), laptops and tablets as the level of comparison to RQ1 and RQ2. Single-user environments are of interest insofar as they are commonly used in support of collaborative processes in many of today's work environments and research designs. In addition to the comparison of LIDs and other media, it is also relevant to account for the varying designs and features of LID environments, for example the use of vertical versus horizontal displays. To do so, we added RQ3 to better understand design features and associated dynamics through which LID-based collaboration benefits materialize.

2.2. Search strategies

In conducting this systematic review, we followed general steps for literature reviews (Booth, Sutton, & Papaioannou, 2016; Cook & West, 2012; Kitchenham et al., 2009): We started by identifying the need for a systematic review and deducing the research questions. This step was followed by the search for relevant studies and an assessment of the eligibility of studies based on previously established inclusion und exclusion criteria (see the description of the criteria below and for the graphical illustration of the process Figure 1). Finally, we analyzed the eligible studies and synthesized them (see Supplementary Data: Appendix A).

FIGURE 1. Process diagram of identification, screening and eligibility of the studies.



We reviewed empirical studies from the most important fields in which such studies on LID are typically published, e.g. HCI, CSCW, CSCL and psychology. To identify relevant articles from leading journals and conferences, the first of our searches involved publicly available and peer-reviewed articles in the Web of Science, Psych.Info, ACM, Elsevier, JSTOR and Springer databases for journal articles and the ACM Digital Library for papers from the CHI conference. The search was conducted in August 2017, with an update in March 2019, and included articles in the English language from the past twenty-two years (1997–2019). The search was specified by combining the terms *interactive display, tabletop, interactive wall, wall display, tabletop interfaces* and *multi-touch* with the terms: *collaboration, group* or *team* or *work* or *education* or *learning* or *CSCL* or *CSCW*. Using these keywords, we searched the field *topic*, which yielded a total number of 916 articles after removing the duplicates. Moreover, papers from the most important ACM HCI conferences (CHI and ITS/ISS) were searched using the same keywords. This search yielded 575 articles.

The 1491 identified articles were assessed to determine if they met the following **screening criteria**, which were carefully chosen to ensure the quality of this review following widely established criteria: (1) *Publication date*: from 1997 through to 2019; (2) *Publication type*: Peer-reviewed journals, CHI or ITS/ISS conference; (3) *Language*: English; (4) *Length*: at least ten pages (this criterion meant eliminating work in progress that reports preliminary results); (5) *Subject*: the research presented in the paper directly addressed collaboration at a LID in the work or educational context.

Based on these screening criteria of the total 1491 identified articles, 668 were deemed to be eligible and were included in the further analysis. During this analysis the full text of the publications were retrieved and reviewed against the following **eligibility criteria**: (1) *Sound experimental* methodology: sound methodological quantitative study with a pretest and/or control group, see Campbell and Stanley (1966). Studies of lower methodological quality were not considered: studies needed to both describe their data-gathering procedures, the study population (e.g. number of participants, gender, etc.), intervention and (experimental) procedure, and all necessary information regarding the statistical tests used (e.g. mean and standard deviation for parametric tests, etc.). (2) *Educational or work settings*: the study took place in a work or educational setting; excluded here were studies of leisure activities or public displays as well as studies comparing different cultures; (3) *Physical setting*: studies needed to include at least one large interactive display; (4) *Collaborative task*: the participants were involved in collaborative work with the explicit goal of completing a clearly defined task (competitive tasks were excluded); (5) *Measures of collaborative work*: papers reporting measures of collaborative processes and/or task-related outcomes were included, whereas studies reporting only measures of system usability and user experience were excluded; (6) *Participants*: studies of groups with special needs (like small infants and autist or geriatric participants) were excluded. After this rather conservative procedure there remained a total of 41 studies reported in 38 articles.

2.3. Sample

The total of 38 articles were finally synthesized with respect to the variables described below (see Figure 2). Articles and papers describing more than one study with different

FIGURE 2. Coding scheme: Categories and subcategories used for analyzing the empirical studies.

Input (RQ3)	Process (RQ1)	Outcomes (RQ2)
Technology affordances; Task and group characteristics; Context affordances	Workspace awareness Verbal and gestural communication; Participation Coordination strategies Artifact interaction; Level of reasoning	Knowledge outcomes: e.g. the extent of acquired knowledge as measured in a test; Task-related outcomes: e.g. effectiveness, efficiency, satisfaction with task outcome Social outcomes: e.g. satisfaction with group's process, established trustworthiness

independent variables were separately scored and referred to as Study 1 and 2. For instance three papers reported two relevant studies each (Buisine et al., 2012; Rogers & Lindley, 2004; Tang, Tory, Po, Neumann, & Carpendale, 2006). The final sample thus consisted of 41 studies.

2.4. Data coding and analysis

The in-depth analyses of the 41 studies involved the reading, re-reading, extracting and summarizing of information on experimental design and empirical results based on the following categories and subcategories: input (influencing factors), collaborative processes and task-related, social or knowledge outcomes (see Figure 2). These categories were extracted from the Input-Process-Output (IPO) model, which proved to be a robust framework for conceptualizing research in HCI, CSCW/CSCL and small group research (Marks, Mathieu, & Zaccaro, 2001; Mathieu, Maynard, Rapp, & Gilson, 2008; McGrath et al., 1993; Pinsonneault & Kraemer, 1989).

In establishing the coding scheme, we followed theoretical distinctions from previous research (Beal, Cohen, Burke, & McLendon, 2003; DeChurch & Mesmer-Magnus, 2010; Fransen, Kirschner, & Erkens, 2011; Marks et al., 2001; Mathieu et al., 2008; McGrath et al., 1993; Pinsonneault & Kraemer, 1989; Salas et al., 2008). The **input** or contextual information category covers characteristics of the LID, of the task being solved and of the group using the LID as well as those of the LID's context of use. These are characteristics that were varied as independent variables in some of the reviewed studies. We considered subcategories of the characteristics pertaining to technology, task, group and context thereby drawing on the widely acknowledged view that group performance depends on the fit between technology (here: direct, multi-touch, multi-user interaction) and the group including its tasks as well as the context in which action takes place (McGrath et al., 1993, p. 307).

Collaborative processes and outcome variables concerned the respective effects of the input at both group and individual level. **Collaborative processes** are defined as "*members' interdependent acts that convert inputs to outcomes through cognitive, verbal, and behavioral activities directed toward organizing taskwork to achieve* *collective goals" (*Marks et al., 2001, p. 357). Included in the subcategories of collaborative processes were thus: participation, workspace awareness, verbal and gestural communication, coordinating strategies, and level of reasoning (see Figure 2). In addition to traditional indicators of collaborative processes, we also included indicators that have generally been neglected by small-group research but have received increasing attention in HCI studies, such as artifact manipulation and interaction.

For **outcomes**, defined as "*results* and *by-products* of team activity" [our emphases] (Mathieu et al., 2008), we considered three subcategories: task-related outcomes, social outcomes and knowledge outcomes (see Pinsonneault and Kraemer (1989) for a detailed description of task-related outcomes and social outcomes). The subcategories *task-related outcomes* cover classic aspects of usability studies with attention to goal achievement. They included measures of (1) effectiveness, namely "an evaluation of the results of performance with no consideration of the costs of achieving the results" (Beal et al., 2003, p. 995) e.g. quantity and quality of ideas produced in a brainstorming tasks, (2) efficiency, i.e. the "the effectiveness of a group with some consideration of the cost of achieving that level of effectiveness, that is, a ratio or factoring in of inputs relative to outputs" (Beal et al., 2003, p. 995) e.g. time on task, number of errors, and (3) satisfaction with task results. The subcategory *social outcomes* refers to the subjective evaluation of the quality of the collaborative process and its effect on future individual behavior, e.g. satisfaction with group's process, willingness to work together in the future, and trustworthiness. Based on the analyzed studies, we also considered a third subcategory, *knowledge achievements*, measured at the individual level as knowledge that participants acquired during the experiment (e. g. number of learned facts).

For all subcategories we classified the effects reported in the studies as positive, negative, null, partial or mixed. Positive means that for all measured indicators of a subcategory there are positive relations reported; negative means that for all measured indicators there are negative relations reported; null means that no significant differences were found; partial means that a positive effect was reported only for some aspects of the same indicator, e.g. significant effect for artifact interaction but only for the second half of the time spent on a task (see Wozniak et al., 2016). Mixed means that distinct effects for the different indicators of the same subcategory were found, e.g. amount of communication and type of utterances (see for example Rogers et al., 2009). The reported effects were extracted and summarized (see Appendix A) and the results synthesized (see Section 3). Regarding the quality of the extraction of the type of effect, half of the selected studies were independently reviewed by the second coauthor and no differences in the interpretation occurred.

3. RESULTS

Below we summarize the effects of LIDs on collaborative processes (RQ1), outcomes (RQ2), and influencing factors (RQ3).

3.1. Collaborative processes

Out of the 41 studies, twenty studies compared LIDs with traditional media (single-user environments and paper). Hence, the comparison of LID-based collaboration processes with collaboration processes attendant to the use of other media was a popular approach in the corpus of studies we examined. Collaboration processes were measured in the reviewed studies using different subcategories including (a) workspace awareness, (b) verbal and gestural communication, (c) participation, (d) coordination flow, (e) artifact interaction, and (f) reasoning levels, which are presented below. Our analysis revealed mostly positive effects of LID use on collaborative processes (RQ1) in comparison with traditional media such as paper and/or single-user environments (see Figure 3).

FIGURE 3. Synthesis of the results for measuring the collaborative processes.

Subcategory	Description/Examples of Measures	Summarized Findings
Workspace awareness	Understanding another person's interactions with the shared workspace; measured through self-reports and indicators based on observations, such as parallel and serial work, the number of interferences and verbal shadowing.	All studies found positive effects of LID over both paper and single- user environments.
Verbal and gestural communication	Measures for verbal and gestural communication, e.g. amount of spoken words, type of utterances, and amount of gestures.	No general advantages of LID in supporting verbal and gestural communication, however studies that compared LID with PCs identified positive effects for LID use.
Participation	Level of involvement of all participants in solving the task, e.g. indexes of equity such as the GINI index.	Inconclusive results because the number of studies reporting positive and negative effects is almost evenly distributed.
Coordination flow	Collective coordination strategies describe the ways in which groups orchestrate, link and integrate individuals' contributions, e.g. measures of group strategies and collaborative styles.	All studies on group strategies and coordinative mechanisms found positive effects for LID compared with traditional media.
Artifact interaction	Measures of participants' manipulative behavior regarding physical and digital artifacts, e.g. adding, modifying deleting notes, sketching.	The provision of shared interactive representations in LID conditions led to more manipulative acts of artifacts than in paper and single-user environments.
Level of reasoning	Measures that reflect the level of reasoning observed in or expressed by group members, e.g. in the form of sense-making activities, reasoning strategies, and mental models.	LID supported groups in establishing a joint conceptual problem space with positive effects reported in comparison to PC conditions. Comparisons to paper environments were much less clear.

3.1.1. Workspace awareness

The "up-to-the-moment understanding of another person's interaction with the shared workspace" (Gutwin & Greenberg, 2004) is considered a crucial factor in team cognition, even though maintaining awareness is often not seen as a goal in itself but is rather viewed as taking a backseat to task completion (Endsley, 2015; Gutwin & Greenberg, 2004). All four studies that investigated workspace awareness found positive effects for the LID environment as compared with both paper and single-user environments (Clayphan, Martinez-Maldonado, Tomitsch, Atkinson, & Kay, 2016; Hwang & Su, 2012; Jetter, Gerken, Zoellner, Reiterer, & Milic-Frayling, 2011) or whiteboard (Clayphan, Collins, Ackad, Kummerfeld, & Kay, 2011). For example, Jetter et al. (2011) investigated a decision-and-consensus task carried out on a tabletop and web interface on a PC and they found that the shared workspace on the tabletop resulted in increased awareness. Participants often worked in parallel, yet they offered unsolicited help and suggestions to one another *in situ*, which sustained the overall workflow.

3.1.2. Verbal and gestural communication

The influence of LIDs on verbal and gestural communication was examined in six studies (Hwang & Su, 2012; Hwang, Shadiev, Tseng, & Huang, 2015; Rogers et al., 2009; Buisine et al., 2012, Study 1 and 2; Tuddenham, Davies, & Robinson, 2009). The majority (n = 5) focused on verbal communication measuring for example the number of assertions, questions and answers. Contrary to general expectations, the results do not confirm the advantage of LIDs use over traditional media in supporting verbal and gestural communication. Three of the six studies (Hwang et al., 2015; Hwang & Su, 2012) reported positive effects for verbal communication especially in consideration of the type of communicative acts (seeking and giving help, making suggestions), which are seen as an indicator of the quality of collaborative work. For example, Hwang and Su (2012) compared the application for an English sentence-making task on a LID versus a PC and they found a higher number of verbal requests in the LID condition. Of the other three studies, however, one study reported null effects (Buisine et al., 2012, Study, p. 1), one mixed, null and negative effects (Rogers et al., 2009), and the last study found negative effects only (Buisine et al., 2012, Study, p. 2). The negative effects reported by Rogers et al. (2009) concerned the quantity but not the quality of verbal communication: Participants in the laptop condition (compared to the LID condition) tended to produce dialogue at a faster rate, but no difference was observed with respect to the number of suggestions, confirmations or queries. This was explained by the need of the mouse-holders in the PC condition to justify their moves, e.g. to disclose to other participants what they were doing or planning to do. By contrast, these explanations were not required in the other conditions (tabletop and tabletop plus RFID-enabled physical objects) because of the enhanced transparency and ability of each group member to interact with the interface on their own. These results raise questions and suggest that a higher extent of collaborative processes might not in itself mean improved collaborative work.

Two studies compared the use of LIDs vs. paper conditions regarding the use of gestural communication (Buisine et al., 2012, Study 1 and 2). In the first study the authors report positive effects, with participants in the LID condition using a more balanced gestural communication than those in the control conditions, whereas in the second study they found negative effects. An explanation for this seemingly contradictory result can be found in the setting used as control condition. In the first experiment the *horizontal* LID (tabletop) was compared to a *vertical* flip chart while in the second experiment a round-table setting was used as the control condition. Two studies (Hwang et al., 2015; Hwang & Su, 2012) reported positive effects of LIDs compared with PCs. Null and negative results were found when LID vs. paper-environment were compared, especially when the physical setting (round-table arrangement) resembled the LID setting (tabletop) (Rogers et al., 2009; Buisine et al., 2012, Study, p. 2).

3.1.3. Participation

A total of seven studies addressed the potential affordance of LIDs to boost equal participation (e.g. participation equity) in groups (Clayphan et al., 2016; Piper & Hollan, 2009; Schneider et al., 2012; Shaer et al., 2011; Buisine et al., 2012, Study 1 and 2; Tuddenham et al., 2009). Participation was determined by counting and comparing group members' contributions (interaction with the interface or turn-taking in communication), by calculating an equity index (e.g. GINI index) or by self-reports. Results reveal inconsistent findings, with certain advantages of LID use over other media. Three studies found positive effects (Schneider et al., 2012; Buisine et al., 2012, Study 1; Tuddenham et al., 2009); one study found mixed positive and null effects (Shaer et al., 2011), two studies revealed null effects (Clayphan et al., 2016; Piper & Hollan, 2009) and one study reported negative effects (Buisine et al., 2012, Study, p. 2).

In the five studies that compared LID to paper (Clayphan et al., 2016; Piper & Hollan, 2009; Buisine et al., 2012, Study 1 and 2) no clear advantage of LIDs over paper environments could be found. Schneider et al. (2012) compared a tabletop interface with a pen-and-paper setting for the collaborative task of learning genetics. They found that turn-taking was much more prevalent in the tabletop condition. Similarly, Buisine et al. (2012, Study, p. 1) investigated the equity of participation in a brainstorming task in a tabletop and flip-chart condition and found significantly more equitable verbal contributions in the tabletop condition. Negative effects regarding the equity of participation in LID conditions were reported in their second study. Buisine et al. (2012, Study, p. 2) report lower equity in the LID condition regarding the indicators of information request, action request, communicative gestures and total behaviors as compared to the paper condition. The comparison between LIDs and single-user environments is very limited as only two empirical studies were identified (Shaer et al., 2011; Tuddenham et al., 2009). Although the results point to positive effects for physical participation (Shaer et al., 2011), more studies are needed to shed light on this issue.

3.1.4. Coordination flow

Beyond the concept of awareness, which is based on an individual's understanding of another individual's actions, LIDs also shape users' collective coordinative moves, i.e. the ways in which groups orchestrate, link and integrate group members' contributions. All six studies on coordination-flow found positive effects of LIDs as compared with traditional media (Clayphan et al., 2016; Hwang & Su, 2012; Jetter et al., 2011; Nussbaumer et al., 2012; Piper & Hollan, 2009; Rogers & Lindley, 2004). LIDs prompt groups to work in a more collaborative manner, e.g. as measured in terms of time spent by group members working on the same issues (Clayphan et al., 2016; Hwang & Su, 2012). LID groups also exhibit higher levels of fluid interaction (Rogers & Lindley, 2004) and allow for smoother transitions between different collaborative styles (Jetter et al., 2011). For example, Jetter et al. (2011) found in their tabletop versus web-interface comparison that collaborative work at the tabletop was characterized by smoother transitions between tightly and loosely coupled interactions. Similarly, in their comparison of LIDs and paper-based collaboration, Piper and Hollan (2009) observed a more serial and less integrated collaboration style in the paper condition, in which one student tended to remain passive while another one worked. Comparisons with both single-user environments (Hwang & Su, 2012; Jetter et al., 2011; Rogers & Lindley, 2004) and paper environments (Clayphan et al., 2016; Nussbaumer et al., 2012; Piper & Hollan, 2009) show higher levels of coordination in the LID conditions.

3.1.5. Artifact interaction

LIDs do not only allow group members to engage with one another in concerted coordination flow, but they offer, too, the opportunity to jointly build and manipulate external representations (digital artifacts). Four studies examined artifact interaction, which involves activities such as adding, modifying and deleting notes as well as sketching. Three of these studies found positive effects (Higgins, Mercier, Burd, & Joyce-Gibbons, 2012; Hwang & Su, 2012; Piper & Hollan, 2009) and the fourth study found no effects of artifact interaction (Wozniak et al., 2016). As compared with paper environments, the use of LIDs led to higher levels of the shared viewing of artifacts (Higgins et al., 2012). It also resulted in an increase in active explorative behaviors during the collaborative task-solving process, with participants in the LID condition more often entering answers instead of looking at an answer key (Piper & Hollan, 2009). In addition, LID use also prompted participants to add more notes and sketch more extensively implying that they engaged more actively with the problem space (Piper & Hollan, 2009). In comparison with single-user environments, positive effects on artifact interaction were also observed, with participants performing more manipulative acts on the external representations (Hwang & Su, 2012). In essence, and despite a limited number of studies, the results show evidence of LIDs prompting higher levels of artifact interaction than paper and single-user environments.

3.1.6. Reasoning levels

Collaborative problem-solving processes depend on group members' ability to establish a joint conceptual problem space (Mercier & Higgins, 2014), or, more broadly viewed, common ground (Clark & Brennan, 1991). In so doing, group members express and share their mental models of the problem definition and the problem-solving strategy. The main argumentation in the analyzed studies was that reasoning strategies are facilitated directly by using shared interactive representations and, indirectly, in that LIDs foster more equitable participation, which in turn amounts to higher levels of reasoning (Wallace, Scott, & MacGregor, 2013). Reasoning strategies were measured for example through the quality of insights expressed through higher levels of articulation and reflection (Shaer et al., 2011), the development of more accurate mental models (Higgins et al., 2012) and of more systematic search strategies (Jetter et al., 2011). Of the six studies that examined levels of reasoning, three found evidence of higher levels of reasoning in the LID condition (Jetter et al., 2011; J. Liu, Qin, Yang, Yu, & Shi, 2015; Shaer et al., 2011), one study found both positive and null effects (Higgins et al., 2012), one study found no effect (Schneider & Blikstein, 2018) while the last one reported negative effects (Piper & Hollan, 2009). That is, all studies which compared LIDs with PC conditions reported positive effects (Jetter et al., 2011; J. Liu et al., 2015; Shaer et al., 2011). Comparisons of LIDs with paper environments were less clear, with studies reporting mixed (Higgins et al., 2012) and even negative effects (Piper & Hollan, 2009). In sum, the effects seem to depend on whether LIDs are compared to PC or paper environments.

In conclusion, the analyses of collaborative processes suggest that LIDs have relatively clear advantages over other media regarding the indicators of coordination strategies, workspace awareness, artifact interaction and reasoning levels (albeit the latter only if compared to PC conditions). The expectations that LID use would positively impact verbal and gestural communication and equity of participation were only confirmed in about half of the studies.

3.2. Collaborative outcomes

The second research question (RQ2) addresses the outcomes – that is the "results and by-products of team activity" (Mathieu et al., 2008) – associated with the collaborative use of LIDs in comparison with traditional media (paper and single-user environments). 16 studies compared the outcomes emerging when using LID with those of traditional media (paper and single-user environments). The outcomes of group activity can be classified into three main categories: (1) *knowledge outcomes*: measured as the enhancement of knowledge gained through the collaborative engagement, (2) *task-related outcomes*: measured as group performance, e.g. quality and quantity, and (3) *social outcomes*: measured as groups' affective reactions, e.g. satisfaction with the process and perceived trustworthiness of the encounter (see Figure 4).

FIGURE 4. Synthesis of the results for outcome measures.

Subcategory	Description/examples of measures	Summarized findings
Knowledge outcomes	Increases in knowledge through collaborative activities; outcomes determined through knowledge tests	LIDs use has positive effects over other media; small number of studies
Task-related outcomes	Task accomplishment or performance; measured as qualitative and quantitative indices applied to the end result of group's activity or the processes leading to it, e.g. quantity and quality of ideas for brainstorming tasks, time on task.	Ambiguous findings; LIDs are at least as good as traditional media for task-related performance.
Social outcomes	Subjective evaluation of the quality of the social encounter, e.g. shifts in attitudes toward others, trustworthiness.	Limited number of studies, tentative evidence suggests the advantages of LID over the use of other media.

3.2.1. Knowledge outcomes

Knowledge gains that arise from collaborative efforts are valuable from the standpoint of lifelong and work-based learning (Kayes, Kayes, & Kolb, 2005) and are of particular interest to the community of Computer Supported Collaborative Learning (CSCL), which specifically examines the development of knowledge and skills as a product of collaborative activities. The analysis suggests clear advantages of LIDs over other media, with five (out of six) studies reporting positive effects (Hwang & Su, 2012; Martin-SanJose, Juan, Segui, & Garcia-Garcia, 2015; Schneider & Blikstein, 2018; Schneider et al., 2012; Shaer et al., 2011) and one study reporting no effect (Piper & Hollan, 2009). The positive effects of LIDs were shown in comparison to paper conditions (Martin-SanJose et al., 2015; Piper & Hollan, 2009; Schneider et al., 2012) and single-user environments (Hwang & Su, 2012; Shaer et al., 2011). One example is the study of Shaer et al. (2011) who compared a LID with a PC environment in connection with the accomplishment of a knowledge task (exploring genomic information, e.g. investigating gene mutations). Benefits to learning and understanding materialized in participants in the LID condition who achieved a higher percentage of correct answers in a survey-based quiz. The authors ascribed the positive effects to LIDs' capacity to enable the exploration of a large number of hypotheses and stimulate reflective problem-solving. To conclude, there is considerable support for the assumption that LIDs lead to greater gains in knowledge, especially in pursuit of problem-solving tasks.

3.2.2. Task-related outcomes

Eleven out of the nineteen studies comparing LIDs to traditional media reported one or more measures related to the accomplishment of tasks. Yet the results offer anything but a clear picture. At best they provide supporting evidence that LIDs are as good as traditional media with regard to task-related performance. Four studies found positive effects (Clayphan et al., 2016; Liu et al., 2015; Rogers et al., 2009; Clayphan et al., 2011), two studies found mixed positive and null effects (Wozniak et al., 2016; Zancanaro, Stock, Eisikovits, Koren, & Weiss, 2012), four studies found null effects (Higgins et al., 2012; Hwang & Su, 2012; Jetter et al., 2011; Buisine et al., 2012, Study, p. 1) and one study revealed negative effects (Buisine et al., 2012, Study, p. 2). The ambiguity of the findings is exemplified by three studies that compared LIDs to paper environments in the performance of a creative task (brainstorming). Although the same type of outcomes was measured (production of ideas as expressed by the number of ideas) the findings vary considerably. Clayphan et al. (2016) report positive effects, Buisine et al. (2012, Study, p. 1) report no effects, and Buisine et al. (2012, Study, p. 2) report negative effects. Studies found also contradictory results for objective and subjective task-related outcome measures. For example, Zancanaro et al. (2012) compared LIDs to the use of PCs in solving a negotiation task (creating a joint narrative on a regional conflict). Although the number of multimedia elements created in the LID condition was higher, the satisfaction with the task outcome did not differ between conditions. Inconsistent results with regard to task-related outcomes, in particular with attention to efficiency, might be explained by the fact that LID technology is still in its infant stages of the type of tasks used in the empirical studies. The lack of effects or even negative effects could be linked to difficulties in preforming the task, as argued by Hwang and Su (2012) who consider that the longer completion time in the LID condition was due to the low performance of drag and drop actions.

3.2.3. Social outcomes

This category has received less attention, with only four studies reporting measures a range of social outcomes. Studies examined the satisfaction with the social encounter and feelings of trustworthiness among group members (Nussbaumer et al., 2012), shifts in attitudes toward others (Zancanaro et al., 2012), and feelings of motivation and enjoyment resulting from that activity (Schneider et al., 2012; Shaer et al., 2011). The results unambiguously show the advantages of LIDs, with all studies reporting positive effects as compared to paper (Nussbaumer et al., 2012; Schneider et al., 2012) and single-user environments (Shaer et al., 2011; Zancanaro et al., 2012). For example, Nussbaumer et al. (2012) examined the accomplishment of a financial advisory task by comparing LID and paper conditions, reporting that clients perceived the adviser in the LID condition to be more trustworthy. Moreover, the ways in which space and information was shared on the LID was found to contribute to an overall increase in clients' satisfaction (Nussbaumer et al., 2012). Despite the small number of studies, these results suggest that LIDs offer a clear advantage over the use of other media concerning social outcomes.

3.2.4. Media-comparison

Differentiating the control conditions, i.e. paper versus single-user environments, can help to illuminate the ambiguous findings regarding collaborative outcomes. In comparison with single-user environments, LID-based collaboration resulted in superior outcomes in four out of seven studies (Hwang et al., 2015; Liu et al., 2015; Shaer et al., 2012; Rogers et al., 2009) and in mixed positive and null effects in one study (Zancanaro et al., 2012) while the last two studies report null effects (Hwang & Su, 2012; Jetter et al., 2011). It can be argued that LIDs slightly outperformed single-user environments in terms of collaborative outcomes, but the comparison of LIDs with paper conditions is more opaque, with three out of nine studies reporting clearly positive effects (Martin-SanJose et al., 2015; Nussbaumer et al., 2012; Schneider et al., 2012), five studies reporting null or mixed positive and negative effects (Clayphan et al., 2016; Higgins et al., 2012; Piper & Hollan, 2009; Wozniak et al., 2016; Buisine et al., 2012, Study, p. 1), one study reporting negative effects (Buisine et al., 2012, Study, p. 2). This is suggestive of the conclusion that LIDs are "only" as good as paper environments.

In conclusion, LIDs have a positive impact on collaborative work in terms of knowledge and social outcomes. They also tend to have positive effects on task-related outcomes in comparison with single-user environments. However, the results are mixed when task-related outcome indicators are compared between LIDs versus paper-based conditions.

3.3. Design and influencing factors of large interactive displays

In the sections above, we presented studies comparing LIDs with other media, particularly with the use of paper and single-user environments. In the next part, we will analyze studies on differences in collaborative processes and outcomes that result from variations within the design options of LIDs (RQ3). The findings are presented according to the following classification: influencing factors resulting from technology affordances (input device, workspace setting and display size, knowledge representation, group orchestration mechanisms), task and group characteristics, and context affordances. In so doing, we account for varying ways in which LIDs can be designed and used.

3.3.1. Technology affordances

A majority of the studies (n = 19) contrasted different input devices and display sizes. The validity of the relatively large number of studies in this category is limited by the variety of influencing factors, which restricts the strength of the individual findings.

3.3.1.1. Input device. The properties of the input device condition refer to the manipulability of digital content, for example devices for direct input (e.g. multi-touch) compared to indirect input (e.g. multi-mouse). Four studies report results on the comparison of multi-touch with multi-mouse or tilt conditions (Homaeian, Goyal, Wallace, & Scott, 2018; Jakobsen & Hornbaek, 2016; Shaer et al., 2011, 2012). The comparison of multi-touch and multiple-mouse conditions (Jakobsen & Hornbaek, 2016; Shaer et al., 2011, 2012) and of *multi-touch and tilt* (Homaeian et al., 2018) show minor improvements regarding collaborative processes. Empirical results suggest advantages of multi-touch conditions in terms of physical participation, cognitive processing and problem-solving strategy (Shaer et al., 2011, 2012) as well as a larger number of coordinative utterances and a lower number of disengagement utterances (Shaer et al., 2012). Further advantages of multi-touch were more manipulative actions of digital content (moving, resizing, rotating) and a greater extent of cognitive activities, with group members spending more time on reflective activities and articulating a larger number of insights (Shaer et al., 2012). Yet two of the studies found only partial or no support for the advantages of direct (touch) versus indirect (mouse) input with respect to awareness and participation. Jakobsen and Hornbaek (2016) reported that, whereas self-reported awareness was higher using the touch interface: the qualitative observation showed less interference in the multi-mouse condition despite the increase in parallel work. With regard to participants' verbal participation, Shaer et al. (2011) found no differences between touch and multiple-mouse conditions.

The effects of varying input devices on collaborative outcomes are ambiguous. Comparing a multi-touch and a multi-mouse condition, one study reports positive effects on learning and enjoyment for the touch condition (Shaer et al., 2011). But another study found negative effects for satisfaction and efficiency in one of the intellective tasks in the touch condition – albeit no differences with respect to the negotiation task (Jakobsen & Hornbaek, 2016). In essence, although there are some differences between multi-mouse and multi-touch conditions, and some papers favor the touch condition, the studies do not allow for any definite conclusions to be drawn regarding input devices.

3.3.1.2. Workspace arrangement and display size. LIDs vary in display orientation (e.g. vertical or horizontal) and size, and they can be part of a multi-device setting in which tablets are used as personal workspaces in addition to the use of a joint LID workspace. The *physical orientation* of the LID (*vertical* vs. *horizontal*) was investigated in two studies (Clayphan et al., 2016; Rogers & Lindley, 2004) which focused on different aspects of the collaborative processes. Rogers and Lindley (2004) showed that group members in the horizontal condition switched more frequently between roles, explored more ideas, and reported higher levels of awareness of each other's actions. Also, Clayphan et al. (2016) reported certain advantages in the horizontal condition, which manifested in more equal interaction. However, they found no differences with respect to group-collaboration strategy and level of interest. In essence, both papers report the collaborative advantages of the horizontal arrangement of the displays; however, these findings also need to be treated with caution in view of the limited number of existing studies.

In addition to orientation, one study suggests that the *display size* might have relevant implications for collaboration. Zagermann et al. (2016) varied LID size (small versus medium versus large) in a sense-making task (solving a hidden plot). The large-display condition was linked to higher levels of artifact interaction and more integrative behavior in terms of structuring and manipulating the digital content. The authors also observed more explorative and playful interactions with the larger display (as expressed in a significantly higher number of movements). However, not all aspects of group collaboration were positively affected. For example, the respective conditions showed no significant difference in their levels of communication, and the larger-sized interfaces went along with reduced eye contact among participants (Zagermann et al., 2016). Furthermore, they found no relation between tabletop size and gains in knowledge. In summary, the results suggest that the size of the display impacts collaborative process indicators, but the evidence is very thin.

A key benefit of LIDs, namely workspace awareness, is grounded in the provision of one, shared workspace instead of facilitating work that is distributed across several screens, which is known as a *multi-device setting* (Rogers & Lindley, 2004). The second aspect was confirmed in a study in which group members found it difficult to maintain awareness of one another's actions when working with two large displays with different orientations (Rogers & Lindley, 2004). However, designs in which a LID was complemented by tablets (individual workspaces) did in fact positively influence users' sharing behavior, though no improvements of task-related outcomes were observed (Wallace et al., 2013; Wozniak et al., 2016). More specifically, these settings significantly increased the number of slide-sharing actions in the tabletop-plus-tablets condition as opposed to the tabletop-only condition (Wallace et al., 2013). Albeit the limited number of studies, tentative evidence points to the advantages of adding personal workspaces to shared ones and also suggests detrimental effects of adding a second (shared) LID.

3.3.1.3. Knowledge representation. The way LIDs represent knowedge appears to be relevant for collaborative work. A study comparing the sole representation of ideas with representations of both ideas and their interconnections (in the form of graphic ropes) for a brainstorming task found the latter condition to be linked to more original ideas and longer trains of thought (Afonso Jaco et al., 2013). However, no differences were observed with respect to the number of ideas generated, the number of trains of thought, or the diversity of ideas (number of semantic categories). A second study focusing on the use of features that allow for the contextual augmentation of knowledge representations and structures also found positive effects for the augmented knowledge representation (Beheshti et al., 2017). This study used a knowledge-construction task (consisting of an electron simulation) in comparing the use of paper, tabletop, and tabletop plus handheld device settings and found better results for the third condition. In this latter condition (tabletop plus) the participants could, in the sense of augmented reality, additionally use a handheld tablet to view electrons in motion and explore how the circuit functioned in situ. This was achieved by zooming in or tapping on a component to inspect its electrical measures. Meanwhile the tabletop-only condition allowed users to view an electron simulation alongside the electrical circuit on the same display. The augmented representation outperformed the other two conditions with respect to the accuracy of mental models and engagement with the task, supporting participants in making meaningful connections between representations (Beheshti et al., 2017).

3.3.1.4. Group orchestration affordances. In addition to features that allow for the representation and manipulation of knowledge, a few studies investigated mechanisms that were geared toward framing social interaction, either by providing ongoing feedback on group processes and outcomes or by pre-scripting the social process. *Mirroring tools* collect information about a group's processes, e.g. the speaking time of individual members (Bachour, Kaplan, & Dillenbourg, 2010) or a group's performance (Chen & Chiu, 2016b) and play this information back to the group, which in turn affects the collaboration. The effects of these feedback mechanisms were positive. They included a greater acquisition of knowledge as produced by the mirroring of group performance (Chen & Chiu, 2016b). Displaying the speaking time of individual members was also beneficial but only in groups that valued balanced participation more generally (Bachour et al., 2010).

Orchestration in the form of *scripts* likewise proved valuable. The use of scripts was found to be an efficient strategy in guiding groups' collaborative process when compared to groups operating in the same setting without scripts. Chen and Chiu (2016a) used scripts that structured groups' interaction and elicited effective group interaction – i.e. asking questions, providing feedback, making suggestions and sharing ideas. Implementing scripts that raise discussion intensity, balance discussion biases (proportion of shared and unshared information) and foster mutual understanding has also been shown to bring higher rates in task solving besides the expected improvement of the collaborative process, e.g. higher discussion intensity, lower bias, higher levels of reasoning (Bause, Brich, Wesslein, & Hesse, 2018).

A subtle but as effective group orchestration affordance can be achieved by designing interfaces so that they reinforce group members' engagement, for example by *offering shared controls* as opposed to separated ones (Morris, Paepcke, Winograd, & Stamberger, 2006) or by providing a *central collection area* (Shadiev, Hwang, Huang, & Yang, 2015). Shared controls contributed to the equity of collaboration (Morris et al., 2006) however with no impact on the amount of verbal communication and in the task outcome (number of times that pictures were correctly labeled). In another study a central collection area increased collaborative interactions (number of requests) and simultaneously reduced the number of exchange errors with a faster time-on-task (Shadiev et al., 2015). To conclude, the results show some positive effects for shared controls and collection areas, thus pinpointing the possible usage of such affordances for regulating and guiding collaborative work.

To conclude, the results point to workspace arrangements as well as knowledge-representation and group-orchestration affordances having relevant implications for collaborative processes and outcomes; yet due to the relatively small number of studies per category, further research is needed to corroborate these findings.

3.3.2. Task and group characteristics

In comparison with technology affordances, other influencing factors, i.e. task and group characteristics, have received less attention. Four studies investigated various task characteristics (Jakobsen & Hornbaek, 2016; Tang et al., 2006; Schmitt, Buisine, Chaboissier, Aoussat, & Vernier, 2012; Liu, Chapuis, Beaudouin-Lafon, & Lecolinet, 2016) and group characteristics were examined as an independent variable in only one study (Martin-SanJose et al., 2015).

Task characteristics (e.g. task type, task interdependency, time pressure) are viewed as critical to understanding and predicting group effectiveness (Straus, 1999), which is also reflected in the present review. The *task type* (e.g. problem solving vs. negotiation) was found to influence both collaborative processes and the outcomes of groups working with a LID. Jakobsen and Hornbaek (2016) found a higher equity of participation for the problem-solving task compared with the negotiation task when using a LID in a posttest within-subjects experimental design with two factors (input method and task type). Yet more studies are needed to understand the differences between other types of tasks, for example problem-solving and creativity tasks.

Task *interdependency*, i.e. the extent to which group members are encouraged or prompted to work together, is another important characteristic that influences collaborative processes (Tang et al., 2006, Study 2; Liu et al., 2016). The same task can be framed as highly interdependent by increasing the joint responsibility for the task outcome, which in turn impacts the collaborative processes. Comparing individual and compromise task-solving strategies with a LID, Tang et al. (2006, Study, p. 2) found differing collaborative styles among groups. Participants in the compromise-route condition, who had to come up with only one solution to satisfy the demands of both travel time and financial cost, spent more time working together than the participants in the individual-routes condition who generated two independent routes, one for travel and one for financial cost. *Parallelization* (loose versus close collaboration) and the availability of shared-interaction support – which was implemented as a parallel layout versus a sequential style – was found to sway data manipulation on vertical displays. More specifically, a close collaboration style (participants were "forced" to perform each subtask together) increased the efficiency of individual pick-and-drops (the movement time for pick-and-drops) in the distant layout as compared to loose-collaboration (where the subtasks could be performed individually) (Liu et al., 2016).

Taking a deeper look at these studies it becomes evident that interdependencies among different types of influencing factors (e.g. task type and technology affordances) should not be neglected and may explain some of the seemingly contradictory results with respect to the role of LIDs in collaborative processes and outcomes. Tang et al. (2006, Study, p. 2) found a significant interaction between technology design (interaction technique: filters versus lenses) and task characteristics (individual versus compromise-route type) insofar as the participants collaborated less intensively in the lenses and individual condition. Regarding task-solving efficiency, there are indications that input type (touch vs. multiple mouse) and task type (negotiation versus intellective) are interdependent since groups were faster in using the mouse as an input device for the puzzle task (intellective). However, no differences were found for the newspaper task (negotiation) (Jakobsen & Hornbaek, 2016). Two different types of tasks were used in this experiment: a negotiation task with conflicting goals and a problem solving task with common goals that required close cooperation. Even if only a few experiments examined task characteristics and the interaction between technical design factors and tasks, the results suggest that task characteristics are likely to influence both collaborative processes and outcomes.

Group characteristics (e.g. group size) were investigated only in one study and the results showed that *group size* (groups of two to twelve members) did not influence learning outcomes (Martin-SanJose et al., 2015). Even though the results do not pinpoint any differences between the size of groups, such results are scarce, and more research is needed to investigate how variations in the size of groups and displays can ultimately affect collaborative processes.

3.3.3. Context

Context (e.g. characteristics of the physical space, organizational factors) can also have "significant consequences over the ordering of the activity of individuals and groups" (O'Hara, Perry, Churchill, & Russell, 2003, p. xxiv). Context was investigated in three studies (Chen & Chiu, 2016b; Mercier, Higgins, & Joyce-Gibbons, 2016; Schmitt et al., 2012). The *physical positioning* of LIDs in the room and that of groups working with the different LIDs in relation to each other can result in qualitative differences in the collaborative processes. Mercier et al. (2016) found that the seating configuration influenced students' behavior, with higher levels of talk in the centered-room condition (where the tabletops faced toward the center of the room to form a circle) as compared to a traditional forward-facing room (where the tabletops faced the interactive whiteboard). Organizational factors, such as *social comparison* and *intergroup competition*, also affected collaborative processes and outcomes. Investigating a brainstorming task with a LID, Schmitt et al. (2012) varied environmental conditions by creating social pressure by mirroring individual activity and thereby showed that organizational factors can change task outcomes. They report an increase in the number and quality of ideas in the social-pressure condition. Chen and Chiu (2016b) found that *intergroup competition* supports higher levels of engagement. Even if the findings drawn on thin evidence, they suggest that, in the design of shared workspaces it is necessary to consider a variety of contextual factors, e.g. location and positioning of LIDs in the room as well as softer factors, such as social pressure and intergroup competition.

To conclude, technology affordances as well as task and group characteristics along with context affordances might well have an influence on collaborative processes and outcomes. There are indications of a positive impact associated with affordances that keep participants more engaged with each other (shared controls, smaller table size, round-table setting) and help to increase the group's meta-reflection (mirroring tools) as well as multi-device settings with a clear delimitation of personal and group space. Research into group orchestration and knowledge representation on LIDs is promising but still in its infancy. Yet the results are underpinned by a limited number of studies and therefore need to be interpreted with caution.

4. DISCUSSION

4.1. LID effects on collaborative processes and outcomes

In order to better understand the effects of LIDs on collaborative processes and outcomes, we reviewed high quality, experimental studies using a coding scheme that draws on established models of team-collaboration (see Figure 2). Half of the studies examined (n = 20) concentrated on the comparison of LIDs and traditional media, such as paper and/or single-user environments (PCs, laptops or tablets). The main advantage of comparative studies is that they evaluate the usefulness of LIDs not in itself but through the comparison of benefits and limitations with alternatives (Buisine et al., 2012). The underlying rationale is that different affordances offered by the media shape collaborative work and outcomes in specific ways as shown in Section 3.1 and 3.2.

4.1.1. LID and collaborative processes

Among the studies analyzed, the conclusion that LIDs support *collaborative processes* was relatively consistent, as positive effects have been reported for several key variables: In sum, LIDs contribute to efficient group collaboration styles, enhance awareness and artifact interaction, produce higher levels of reasoning and help develop accurate mental models – better than paper and single-user environments. However, according to the findings, not all collaboration processes benefit from the affordances offered by LIDs. For example, the reviewed studies revealed mixed results with regard to verbal and gestural communication. Whereas beneficial effects were reported in the comparison of LIDs with single-user environments, no clear advantage was found for settings in which LIDs were compared with pen-and-paper environments, particularly when a round-table arrangement was employed (e.g. Buisine et al., 2012). Results are also inconclusive concerning participation patterns and the equity of contributions, i.e. in terms of turn-taking and physical participation, regarding which an almost equal number of studies with positive and negative effects were found.

The comparable effects of LID and pen-and-paper environments on verbal and gestural communication or participation might conceptually be explained by the two similar sets of affordances that these media share – particularly when compared with single-user environments: Firstly, the (physical) table arrangement and, secondly, multiple entry points, i.e. the number of input devices or touch points that users have at their disposal when interacting simultaneously with the interface. Findings from the present review suggest that it is the number of entry points which impacts collaborative processes and not the modality of the input, i.e. touch vs. mouse. While touch – as compared with one-mouse conditions – generally improves collaboration, the comparison of multiple input devices is more ambiguous: multi-touch does not necessarily lead to qualitatively better collaboration processes than multi-mouse. The studies reviewed suggest that it is the combination of *multiple entry points* (touch or mouse) and the *around-the-table* affordance which amounts to improved collaborative processes when working at a LID. This affirms Scott et al.'s (2003) suggestion, who pointed in their review to the role of simultaneous user interaction on LIDs as a distinguishing feature, noting, however, that LIDs at that time tended to limit users' interactions by having them share one input device. More recent research also shows that it is LIDs' affordance of featuring simultaneous collaboration which makes them superior to traditional pen-and-paper settings (see Piper & Hollan, 2009). This conclusion strengthens the recommendation of Bellucci et al. (2014) who say that the design of LIDs should not concentrate overly on the input modalities, i.e. touch vs mouse, but on the ways in which different modalities can "cooperate in the same ecosystem" (p. 32:23).

As already discussed, LIDs outperform paper environments in some respects, and this also warrants interpretation. Drawing on the findings from this review, one could argue that it is particularly the integration of three affordances that shape collaboration on LIDs and make it more effective than paper-based collaboration. These are the aforementioned affordances regarding *multiple entry points* and the *around-the-table* setting, in connection with the affordance of interactivity. Although a pen-and-paper setting offers an around-the-table setting, it constrains the level of concerted artifact manipulation. On a LID, users can simultaneously and easily change digital artifacts at low communication costs. That is, they can create external representations, e.g. by drawing or writing, and moving them around whilst being able to monitor other members' actions. In other words, the interactivity offered at LIDs permits users' joint, synchronous and synchronized engagement with the artifacts. As the present results show, LIDs permit higher levels of awareness combined with increased artifact interaction and coordination flows that allow for more parallel work compared with the more serial collaboration style typically featured in traditional environments.

4.1.2. LID and task, social and knowledge related outcomes of group work

In addition to processes, this review has also examined the effects of LIDs on social, task- and knowledge-related *outcomes* of group work. This is an aspect that previous reviews have examined only to a limited extent. The present results on knowledge outcomes corroborate the previous review of Higgins et al. (2011) from classroom contexts, who conclude that "multi-touch tables influence the way learning groups interact, with potential for influencing learning outcomes" (p. 528). The authors argue that tabletops in classrooms can support learning. This review extends this rationale, not only by incorporating a larger number of studies but also by suggesting that the positive knowledge effects of LIDs use also unfold outside classic formal education settings. This can be relevant for knowledge intensive organizations, too, which need to ensure the co-creation of ideas and the joint problem solving of actors along the value chain (Aarikka-Stenroos & Jaakkola, 2012). This is supported for example by LIDs' capacity of enabling the exploration of a large number of hypotheses and stimulate reflective problem-solving (Shaer et al., 2011).

By contrast, the findings regarding task-related outcomes of LID-based collaboration are inconsistent and indicate no clear advantage of LIDs over traditional media. It is again the differentiation of the control conditions, i.e., of pen-and-paper and single-user environments, that can help to further interpret the underlying dynamics. LID-based collaboration resulted in superior outcomes compared with single-user environments (Hwang et al., 2015; Liu et al., 2015; Shaer et al., 2012; Rogers et al., 2009), but, for particular types of outcomes, it did not prove superior to paper environments. The similar effects of pen-and-paper and LID conditions on outcomes in some categories, e.g. higher number of ideas and more categories (see Clayphan et al., 2011) – can be explained by the affordances that they have in common, i.e., the around-the-table setting and multiple entry points.

4.1.3. LID and the relation between process and outcome

Another relevant aspect in understanding the role of LIDs for collaborative outcomes is to consider the mediating role that collaborative processes take in facilitating outcomes (Mathieu et al., 2008). Even though the quality of collaborative processes has often been linked to higher group performance (Mathieu et al., 2008), this relationship is not necessarily a straightforward one. Groups are complex systems and highly dependent on a series of contingent factors: "a single basic process can lead to both good versus poor performance, depending on the context in which that process is enabled" (Kerr & Tindale, 2004, p. 641). For example, the amount of communication leads to better performance in some contexts but can be detrimental in others, e.g. by reducing the allocated time for individual production (Kraut, 2003). Even though most of the studies reviewed here report both process and outcome measures, they did not investigate the mediating role of collaborative processes on outcomes. Only four studies did so and all reported a positive relation

(Hwang & Su, 2012; Schneider & Blikstein, 2018; Schneider et al., 2012; Wallace et al., 2013). Without considering the relation between collaborative processes and outcomes in a comprehensive model, the way in which technology conditions the development of collaborative outcomes cannot be fully understood, and this is clearly a path for investigation to be considered in future work.

4.2. Understanding the design space of LIDS

4.2.1. Effects of LID design

A third goal of this paper is to address the specific affordances of LIDs that impact collaborative processes and outcomes. This review examined a plethora of design LID-based modifications which have been implemented and tested to date. These can be basically grouped into three categories: technology affordances, task and group characteristics, and context affordances.

The range of **technology affordances** provided by LIDs is very broad covering the physical design of the workspace (e.g. adding personal spaces and control areas), interactional affordances (e.g. augmented reality and manipulation options of external representations) and functionality that explicitly guides group behavior (e.g. mirroring tools and scripts). The findings of the reviewed studies point to specific affordances that enable effective collaboration. Understanding what affordances can enable which aspects of the collaborative work translates in actionable design decisions.

The first type of affordances relates to the *physical design of the workspace*. The arrangement and number of entry points as well as the use of partitioned workspaces have been studied more extensively and thus allow more robust conclusions. An appropriate *number of entry points* afford users' joint, synchronous and synchronized engagement with the artifacts as the comparison of the LIDs with single-user environments reveal (Hwang et al., 2015; Liu et al., 2015; Shaer et al., 2012; Rogers et al., 2009). These translate into higher levels of awareness, increased artifact interaction and better coordination flow, and thus need to be implemented accordingly when designing interfaces for LIDs. Touch vs. multiple-mouse input devices were explored in various studies (Jakobsen & Hornbaek, 2016; Shaer et al., 2011, 2012), however the inconsistent findings are difficult to translate into design moves that would enable collaborative work as they are not as conclusive.

Affordances which are created by *partitioning the joint workspace* or by adding additional personal spaces to a joint space help facilitate a group's coordinative processes because they clarify individual responsibilities which can otherwise result in ambiguity. This is largely supported by the results of the reviewed studies. For example, results have shown that multi-device settings which consist of a joint space (LID) and individual workspaces (tablets) positively influence users' sharing behavior (Wallace et al., 2013; Wozniak et al., 2016). Shared control or collection areas, similar to personal spaces, have the potential to clarify individual responsibilities, keep participants more engaged with each other (Morris et al., 2006), and to increase collaborative interactions (Shadiev et al., 2015). The differentiation between personal and joint work areas can alleviate groups' needs for explicit coordination, and so groups can achieve a more fluid but still concerted coordination between its members. Coordination between team members happens implicitly as does the fluidity of sharing – which is defined as the ease with which roles can be switched or as the process of interweaving user actions (Hornecker, Marshall, & Rogers, 2007) – emerges as a function of the carefully designed workspace arrangement.

Affordances for interaction reach beyond touch or mouse input. One aspect is augmentation. Conceptually speaking, the benefits offered by an "*augmented LID*" can be explained by the scaffolding mechanism, which "takes the form of externalizations of cognition that directly support team-level processes by helping to mediate and support the interaction between individual and team-level cognitive activity" (Fiore & Wiltshire, 2016, p. 11). Technological scaffolds help group members engage more with each other through the discussion of information and the revision of ideas (Fiore & Wiltshire, 2016; McLoughlin & Luca, 2002). Putting an augmented reality layer upon an interactive tabletop has led to richer forms of engagement as compared with the classic LID condition (Beheshti et al., 2017).

The affordances of LID which provide opportunities for *joint external representations* (i.e. information archive mitigating the demands made on memory) make them cognitive tools which enable effective group work. Groups need to jointly create and alter external representations in order to mitigate their cognitive processing (Fiore & Wiltshire, 2016; Wilson, 2002). For example, the 'trains-of-thought' brainstorming interface implemented by Afonso Jaco et al. (2013) affords offloading, i.e. making the environment part of a distributed cognition setting (Wilson, 2002) in order to reduce cognitive load. The visualization of trains-of-thought in this brainstorming interface helps improve the production of ideas in terms of both quantity and quality by linking semantically related concepts (Afonso Jaco et al., 2013). Showing links between semantically related concepts activate concepts in people's long-term memory and thus offload and stimulate cognition for higher creativity (Afonso Jaco et al., 2013). Such affordances make up for the limited human capacity to store and access any information that might be momentarily unavailable (Fiore & Wiltshire, 2016).

Mirroring tools and scripts are based on affordances that go beyond the mere physicality of the workspace and impact group work by simplifying coordination and intensifying individual engagement of group members. While personal workspaces and shared control areas implicitly clarify individual responsibilities, scripts and mirroring tools explicitly regulate group behavior and help reduce the cost of coordination in groups, which is known to lead to production losses (Kraut, 2003). Mirroring tools can strengthen group members' motivation, participation patterns, engagement (Bachour et al., 2010) and learning achievements (Chen & Chiu, 2016b). These affordances have been put in the investigative limelight particularly by the CSCL community (e.g. Bachour et al., 2010), but could also prove to be important in the fields of HCI and CSCW, in particular in the study of effective LIDs use. As an integrative part of LID design, scripts lead to the internalization of metacognitive retention and retention in terms of knowledge more in general (Chen & Chiu, 2016a) and thus impact group collaboration.

4.2.2. Characteristics of the task, the group and the context

Less apparent in their effect on collaborative processes and outcomes are the characteristics of the task, the group and the context in which LIDs are used. Evidence found in the studies reviewed suggest that these influencing factors impact collaborative work at LIDs and these elements can can considerably influence group collaboration. In their review, Scott et al. (2003) already pointed to the relevance of task specific differences by finding the "best display configuration for a particular task and user group needs" (p. 173). The present analysis suggests that this remains an important but still under-researched issue, with some research pointing to the necessity of adapting workspace settings according to the task (e.g. Jakobsen & Hornbaek, 2016). Other issues include context factors, such as social comparison and intergroup competition, which have shown to shape task outcomes, for example in terms of an increased number and quality of ideas which are produced under the social-pressure condition in a brainstorming task. These influencing factors have shown to condition the ways in which groups engage with a task, for example by increasing intragroup competition (Chen & Chiu, 2016b) and thus need to be carefully considered in further empirical research. While the results on task, group and context do not offer definitive design guidelines, they reiterate the relevance of these factors and should encourage future thinking regarding how LIDs should be fitted in a large ecosystem.

4.3. Limitations and directions of future research

This review is based on a systematic analysis of crucial journals and conferences and has sought to consolidate the evolving field of LID research. Yet a number of limitations related to the methods and the corpus of studies need to be acknowledged, which offer pointers for future research. Firstly, while the review summarizes the use of LIDs over a period of twenty years, the rapidly changing technological landscape renders the findings a mere snapshot in time, and further research needs to account for the ongoing technological development in this field. This is particularly relevant as displays are moving from labs into the field, especially work and learning settings where new usage scenarios and applications emerge. Secondly, although the search was carried out in a systematic manner and resulted in an initial number of 1491 articles, the body of literature we discovered was not exhaustive, as some conferences and gray literature (e.g. project reports) were not taken into account. With attention to the highly fragmented field of research, the use of specific search terms might have excluded relevant articles that labeled their research in different ways.

Thirdly, the methodological quality of published studies is another concern. Of 668 articles considered for the review based the screening criteria, 630 were deemed not eligible for the review. The main reason was the lack of experimental methodology in those studies. (Many papers focus on technological innovation.) The exclusive analysis of experimental research is indicative of the robustness of certain findings in this review. However, at the same time, the relatively small number of experimental studies in certain categories also presents a limitation. While both technological developments and observational studies are needed to deepen our understanding of the role of LIDs in collaborative work, future research should incorporate systematic experimentation to further substantiate the current evidence. This is especially important for influencing factors like task and group characteristics as well as context affordances, which are underpinned by a very limited number of articles. Similarly, a topic worthy of future investigation concerns the interference caused by the various influencing factors and how the combined effects of affordances can be leveraged to improve the workspace setting.

Previous reviews (Scott et al., 2003) offered the advice to use traditional media as control condition and this has also been the motivation for the research questions one and two, which, we feel was a worthwhile endeavor. The research analyzed clearly shows the advantages of LIDs over traditional media (particularly single-user environments). In addition to clarifying some of the inclusive findings outlined, future research should focus particularly on design and context variations within LID use and how they help groups *coordinate joint activities* and support them in the *completion of a task*.

The need for robust evaluation methodology, particularly regarding the measures of collaborative processes, has also been pointed out in previous reviews (Scott et al., 2003). This is an avenue that still requires further exploration, together with the need to corroborate outcome categories for which we found inconclusive evidence. We would like to point to another area, the relationship between collaborative processes and outcomes, which was only addressed in few studies (Hwang & Su, 2012; Schneider et al., 2012; Wallace et al., 2013). As collaborative processes have a mediating impact on outcomes, researchers may well employ robust frameworks from small-group research such as the *Input-Process*(Mediators)-*Output* model (Mathieu et al., 2008; McGrath et al., 1993; Pinsonneault & Kraemer, 1989) which take this relation into account and test these models with adequate statistical models, e.g. mixed or multi-level models. In so doing, the common fate of the participants is taken into account, as did Zagermann et al. (2016) in their recent study. Finally, we encourage future research to use nuanced and corroborated measures of collaborative processes (such as verbal and gestural communication) and make implicit assumptions explicit. For example, the amount of communication can be both a positive and a negative indicator, depending more on its content than on its quantity.

5. CONCLUSION

The main contribution of this systematic review is its synthesis of the fragmented field of the use of LIDs for collaboration, summarizing empirical evidence and pointing to avenues for future research. The analysis of 41 studies generally affirms the positive impact that LIDs can have on collaborative processes and outcomes. However, the picture is nuanced, and the results show that LIDs are no universal solution that improves the multifaceted aspects of group work and outcomes in itself. With regard to collaboration processes, the findings suggest a relatively clear advantage of the use of LIDs over classic forms of collaboration, in particular over single-user environments, as measured through workspace awareness, coordination flow, artifacts interaction and reasoning. LIDs' impact on participation patterns and communication processes and is yet unclear. With attention to collaborative outcomes, positive effects of LID use were identified for knowledge gains and enhanced social indicators, and mixed effects for task-related outcomes, which is one key area for future research. Even though most of the studies reviewed report both process and outcome measures, they fail to investigate the mediating relationship between these two categories, which is an important avenue for future research. Emerging empirical evidence points to the effects of different design factors and the use of LID, spanning a wide range of affordances. Although empirical studies mostly focus on diverse technology affordances and the findings are not always conclusive due to the limited number of studies in each category, they can offer important guidelines for the design of LIDs for both work and learning settings. There are indications that affordances which support the engagement of group members (shared controls, around-the-table settings), group members' meta-reflection (mirroring tools) as well as multi-device settings with a clear separation of personal and groups spaces are associated with positive effects, which require further corroboration by future research.

NOTES

Supplementary material. Supplemental data for this article can be accessed here.

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