# Six considerations for designing and evaluating collaboration in immersive environments

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Figure 1: Different persons collaborating to solve a visuospatial task in a mixed-reality environment. During collaboration, a person does not only interact with the environment, but also with other persons in the environment. For example, by referencing objects in the environment, by communicating aspects of the task, or by exploring the environment from different perspectives. This makes designing and evaluating collaborative immersive environments a demanding, multifaceted task. The figure is an adaptation from previous work, where pairs of two were asked to perform visual graph analysis tasks in mixed reality [19].

## Abstract

Persons use and respond to various cues and behaviors as part of their daily communication and information exchange with others. When these are obscured or obstructed by the technology, users tend to experience rifts in collaboration. For this reason, we discuss different group factors and their role in collaboration in immersive environments. By including perspectives from visual and immersive analytics, embodied interaction, social psychology, and collective behavior, we identify common motives in literature that deserve the designer's attention. We list six considerations for designing and evaluating collaboration in immersive environments. The collection of these considerations could serve to inform future research on the topic.

**Index Terms:** Collaboration, immersive environments.

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## 1 Introduction

With interconnected display and interaction technology becoming ubiquitous, collaboration is seen to migrate more and more to virtual environments. Whether in a virtual environment or not, the consequences of collaboration and group interaction can be described easily as far-reaching. To illustrate this, we give two examples. In the first example, evolutionary biology posits that the computational demands of interacting in large, complex societies had driven the selection of large brains in primates [13]. In the second example, psychology tells us that among others, collective creations are known to emerge from collaboration [40]. As far-reaching as these examples may be, it may not be immediately clear how any of these relate to collaboration in immersive environments. In short, if there are rifts in group interaction, users are bound to face challenges. Collaboration should not be (additionally) hindered by the design and implementation of the environment. Therefore, it is important to have a layered understanding of the sub-compositions that comprise the task of designing and evaluating collaborative environments. Embodied interaction [11] nicely demonstrates one such integrative approach. Embodied interaction draws on a broad spectrum of environmental and social factors to facilitate an effective participation across increasingly capable graphical interfaces, e. g. mixed or virtual reality (MR/VR) stereoscopic head-mounted displays (HMD). To achieve anything like this successfully, solutions underpinned by a set of diverse perspectives are necessary.

Collaborative environments are defined as capable to support the simultaneous flow of information among participants through space and time [4, 26], while immersive environments are required to predispose psychological immersion [35]. We argue that factors, such as group interaction and group decision-making, deserve careful attention while design choices are being made. In the remainder of this paper, we hence discuss *group factors* that should be considered when designing and evaluating collaborative immersive environments.

Sensemaking, decision-making, and problem solving are higher-level cognitive processes, and a common focus for visual [8] and immersive analytics [35]. For this reason, this paper will consider mainly those instances of collaboration where the shared goal is to explore and analyze data. Other applications, such as for collaborative learning or collaborative creativity, are therefore potentially out of scope. The idea for the paper originated after discussions with researchers in the area. In the writing of the paper, we reviewed relevant studies, reviews, books and book chapters from visual and immersive analytics [8, 22, 26, 35, 16], embodied interaction [11, 12], social psychology [45, 31, 21, 34], and collective behavior [46, 29]. Following discussions among the authors, six considerations for designing and evaluating collaboration in immersive environments were derived based on current empirical work.

## 2 Related Work

For visualization [26], visual analytics [8], and immersive analytics [16], collaboration has remained something of an enigma. In immersive analytics [35], where one focus is the validation of immersive environments for collaboration, collaboration stands as a grand challenge [16]. Collaboration is usually characterized based on space and time [3, 26, 28] and defined in relation to the environment [3, 26]. Characterizations based on group attributes can also be found, however, are less common. Hackman and Katz [21] outline synchronicity and responsibility among some of the group attributes. Then, collaboration differs based on whether responsibility is attributed predominantly to the individual or to the group as a whole. In the former, collaboration induces a team, i. e., individuals with assigned roles and responsibilities, whereas in the latter, collaboration results in a group. Across scales, a collective arises from the repeated interactions at the level of the individual [46], whose behavior is by no means independent.

Visual representations are put to collaborative use to obtain additional understanding, beyond that of individual exploration [26]. To achieve this, Isenberg et al. [26] summarized seven challenges and research directions. Heer and Agrawala [22] described 24 design considerations for collaborative visual analytics, which among others relate to common ground and awareness, division and allocation of work, and identity, trust, and reputation. Ens et al. [17] outlined five research directions for MR collaborative systems. Considerations for the design of collaborative environments that have been identified and studied in literature further include presence disparity [47], collaborative coupling [48], interference [24], icebreaking [10] and others. Social factors, such as social perceptiveness [50] and subjective confidence [29], could play a bigger role.

## 3 Considerations for designing and evaluating collaborative immersive environments

In the following, we introduce each of the six considerations separately and discuss what the implications for designing and evaluating collaborative immersive environments are.

**Nominal groups are a useful experimental design technique.** Nominal groups [9, 21, 23, 45] can be used to gauge the effectiveness of groups, however, are not commonly used in the evaluation of collaborative immersive environments. Nominal groups too comprise of group members, but group members do not have to interact with each other. That is, members' contributions are collected individually and evaluated as a group only after the task or sub-task is completed. During evaluation, the harmonization of contributions could be performed in different ways [19, 45, 9]. By scaling the size of the nominal group, one can see parallels with concepts, such as wisdom of the crowds [18], swarm intelligence [5], and crowdsourcing, as manifestations of the law of large numbers.

In experimental design, nominal groups can be applied as benchmark to help test if collaboration in the environment under study performed reasonably well. The benchmark's power should scale with the size of the nominal group, i. e., if responses are sufficiently independent (by the central limit theorem). A nominal group in the experimental design by definition normalizes for group size, which is not the case when testing only against the individual. The use of nominal groups thus serves to disentangle collaborative from aggregate effects. Consequently, the design of immersive environments should (try to) optimize for collaborative effects, such as assembly bonus effects in groups [45, 23, 31]. Depending on how the nominal group is harmonized, properties, such as "more than the sum of the parts" [46], can also be tested. What social psychology tells us is such effects are generally difficult to attain. For example, an immersive environment alone does not imply the emergence of collaborative effects [19]. Still, collaborative immersive environments, when designed appropriately, hold promise to achieve this.

*Any comparison involves at least 4 persons.* An immediate corollary for the study design with nominal groups is that the required number of persons is twice the group size. However, the comparison against individuals can be "for free", which recovers some of the feasibility. For example, four persons are required to accommodate a collaborative and a non-collaborative pair. Two of the four are assigned to the collaborating pair, whereas the remaining two to the non-collaborating pair. Of the latter two, one is assigned randomly to also be the individual for a second comparison against the collaborating pair.

**Designing immersive environments to optimize communication.** Communication is the process of exchanging information among individuals (ideas, insights, etc.). Different approaches have therefore aimed to improve verbal and non-verbal communication, e. g., by means of suitable interfaces [38] or via group process techniques [9]. In the context of shared spaces, the term awareness [12] has established itself for non-verbal, indirect communication. The aim of improving communication can also be formulated the other way around, that is, to reduce the process loss [45] during collaboration. In Steiner's terminology [45], a group with less "process loss" is closer to utilizing its full potential for the given task and, tweaking the concept slightly, the given environment. Process loss, for example, points to the reason why nominal groups outperform in analysis tasks: an efficient mechanism of communication, requiring a grand tallier of sorts. Lastly, how well information spreads via communication is regulated by the environment, e. g., visual clutter hinders communication.

Communication thus circles back to embodied interaction, and direct manipulation in particular. As an example for direct manipulation, a multiplicity of virtual objects lends itself to pointing [22] and can be used to direct awareness in any 3D environment. By designing all opportunities for action "out in the open" [11, p. 13], the process costs for both the individual and the group are reduced. If interaction interfaces are also generic in kind, interaction may become grounded across tasks and environments that have similar constraints [7]. Following some critical-mass adoption [25], social protocols [6, 36] could emerge at the level of a class of systems or environments. Like how practiced groups can communicate more easily [31], such *sustained collaboration* can free communication from the intricacies of one particular environment. Idealistically, a collaborative environment should induce sustained collaboration in its users, without them having to spend the time to achieve this.

Designers should also be aware of the fact that group members tend not to share all of the available information at their disposal, i. e., the so-called hidden profile paradigm [44]. Hence, collaborative immersive environments could be designed to aid communication and evaluated to support the flow of information. We conclude with an example of supporting verbal and non-verbal communication, e. g., to convey tacit knowledge between group members [37]. Deimos [33] is a grammar for the creation of embodied immersive visualization morphs. Through morphing, users are able to switch between different visualizations of the same data as if the visualization is part of the environment.

**Less is more.** Designers know this phrase well. For collaboration, the assumption is that contributions, albeit less in number, should be better validated after having undergone discussion [23]. This is because contributions obtained sequentially (synchronously) are fewer than those obtained in parallel (asynchronously), i. e., per unit of time. A superior validation is not guaranteed though, since individualistic or strategic behaviors, in animals [43] and humans [31] alike, may sway the group's decision-making. The cost, or even outright inability [41], to maintain an accurate shared mental model [34] might suggest why less is more, i. e., the group intuitively tries to optimize this cost.

In immersive environments, it can become difficult to exchange and keep track of information due to the added layer of interaction and visual abstraction. From this point of view, the design of collaborative immersive environments could focus on simple, effective, and actionable interfaces and visual representations, emphasize embodied interaction, and consider appropriate annotations for error identification. Any annotations should be light and transient [48]. Allowing for transitions between close and loose collaboration has also been shown to aid collaboration [12, 48].

**Immersive environments capable of coordinating perceptual differences.** Perception refers to how sensory stimuli are interpreted and integrated for use in cognition, emotion, and behavior. Different visual cues [49] can be responsible for the emergence of different behaviors, e. g., for human decision-making [2], the role of neighbor-tracking in locust marching behavior [41] and the perception of cues in relation to the self in cleaner fish [32]. Naturally, individuals are expected to differ in their perception and perception is expected to differ depending on the environment [49]. This is notable, since perceptual differences culminate in a diversity of perspectives [2], which is a strength and a feature of groups, and teams in particular [21, 50, 29]. Individual differences also determine the group and team composition, i. e., homogeneous or heterogeneous, which are known to interact with the task type [21, 45].

For immersive environments, the group composition could reflect an asymmetry of roles, expertise, experience, and skill level. The perceptual abilities (see, e. g., teams) and the subsequent processing and build-up of a mental map can thus differ [1, 11, 30]. On the one hand, such differences might add diversity in reasoning that could improve results, but on the other hand, additional effort in coordination, communication, and consensus-finding might be required [20, 48]. Considering how perceptual differences might be coordinated, several design questions arise. For example, could immersive environments be tailored to the collaborators' individual perceptual differences? In certain cases, individually-tailored collaborative environments seem clearly desirable, while in other cases, the design choice is much less clear or feasible. For example, the VRxD system [39] aims to strike a balance between the two by placing users in each other's shoes to support different levels of mutual awareness. The inclusion of individually-tailored interfaces is also complicated by collaboration itself. If mutual awareness is not well maintained [20], group dynamics and group interaction may be affected. The sense of flow, and hence perceiving immersion, could differ for groups [19], which implies interfaces should not restrict group interaction.

It may not be enough to provide annotations to express what is perceived, additionally provenance could help express how it was perceived. But provenance may not be enough also, then an externalization of the collaborator's mental map could help answer why it was perceived. Each of these design choices should not be considered in isolation, but also in terms of awareness and group dynamics. For example, if group dynamics are suboptimal, perceptual differences may become suppressed and even groupthink [27] may occur. In contrast, by expanding perception group members could attain *distributed perception*, analogous to distributed creativity [40] otherwise not possible individually, that emerges from the coordination in the immersive environment.

**Designing for emergent properties in collaborative immersive environments.** Consensus is naturally emerging in small groups [42], and reaching consensus can even be necessary for certain tasks, such as problem-solving and decision-making tasks [34, 29]. Leadership can also affect how consensus is reached across groups of different sizes [14, 50]. In teams, where group members have specific roles [21], e. g., for visual analytics tasks [8, 26], the group dynamics that affect consensus-reaching are different. Reaching consensus, however, does not always correlate with group performance [15].

Along with consensus-reaching, group interaction represents another emergent property of collaborating groups. Although trying to explain emergent properties with reductionistic approaches has been criticized in psychology [40], summarizing group interaction in broad terms is nevertheless useful. The course of small-group interaction is usually as follows: 1) a gradual expansion of common ground [7, 22] can be observed, which is followed by 2) a phase of mixed-focus collaboration [20] during which any number of ideas and insights are shared, until finally, 3) a build-up of trust may occur. Based on the degree to which group interaction is required, collaboration can be tightly or loosely coupled [48]. With time, group interaction is expected to become more efficient, thereby hypothetically converging to a local optimum for the given group, task, and environment. In this sense, group interaction is self-convergent.

The design of collaborative immersive environments should not hinder, but account for consensus-seeking, and support the emergence of fluid group interaction, e. g., with less interferences [24]. When consensus is necessary or known to be beneficial, consensus-reaching could be supported as part of the design [22]. Mechanisms for detecting, flagging, and allowing dissensus could also be incorporated as part of the design to tackle extreme forms of group consensus, such as groupthink [27]. Preparing and utilizing local copies before or during collaboration could mitigate faulty consensus and improve performance. Explicitly designing for close and loose collaboration [12, 48, 39], e. g., based on space use in the collaborative immersive environment, could be a step in this direction. Group interaction could then focus on sharing insights and resolving conflicts directly.

**The trade-offs in collaborating groups.** While teams and groups vary in size and complexity, the ability of individuals to engage in interactions has been identified as a crucial evolutionary [13] and behavior-forming [41] factor. For designers, the users' past interactions need to be considered for their influence on understanding the current system [11, p. 131]. But these interactions are generally not continuous over the entire collaboration [12, 48] and their initiation and type can even serve as a valuable communication mechanism during collaboration [29]. Collaboration in the group is subject to various trade-offs from the perspective of the individual, which designers should not ignore.

As a result, collaborative immersive environments should incorporate features that are simultaneously appropriate for individuals and groups [20]. For example, an adaptive visualization supports individually-tailored visual analysis, but it does not necessarily convey mutual awareness. In environments where both are supported, different organizational schemes could be employed on demand to leverage the strengths and trade-offs of collaborating and nominal groups and teams, as well as individuals.

## 4 Conclusion

Open questions regarding the role of memory, perception, attention in collaboration require more research. More recently, research has expanded to operationalize and study the effects of physiological measures. Physiological measures, such as EEG, heart rate, or skin conductance, as well as combinations thereof, could see increased adoption in both the design and evaluation of collaborative immersive environments.

Here, we presented six considerations for designing and evaluating collaboration in immersive environments. These are neither final, nor exhaustive, but an attempt to capture the status quo from several different perspectives. As such, the resulting collection of considerations could serve to inform future research on the topic.

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