Measuring multimodal collaboration in immersive environments for problem-solving in education

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Work environment / Laboratoire d'accueil

This work will be carried out mainly at the LISN laboratory, within the ILDA Inria Paris Saclay research team (https://ilda.saclay.inria.fr/).

Abstract / Court résumé

The importance of collaborative distance learning and problem-solving was particularly highlighted by the global pandemic crisis. Immersive technologies, such as Virtual Reality (VR) headsets, have the potential to provide some of the benefits of face-to-face learning and problem-solving. But to understand the impact of VR and other immersive technologies on learning and problem-solving, we need to consider ways of measuring it. This requires us to consolidate existing work from different domains: computer-supported cooperative work, with a focus on collaboration using immersive technologies (such as in VR or using multi-display environments), and on collaborative problem-solving, a topic that spans disciplines such as education. The goal of this thesis is to first collect *measures* that attempt to capture different aspects of collaboration and that are often multimodal in nature. And to then validate these measures in diverse immersive problem-solving and learning settings. Our goal is to provide the community with a set of existing or adapted measures that are well adapted for measuring the impact of collaboration.

Short description of the group and lab / Brève description du groupe de recherche laboratoire d'accueil :

The supervision team is made up of three complementary profiles. Arnaud Prouzeau (CR Inria Saclay) is an expert in VR and collaboration. Anastasia Bezerianos (PR Université Paris-Saclay) is an expert in visualization and decision-making. Audrey Serna (MCF INSA Lyon) is an expert in learning through collaborative and gamified digital technologies. A.Prouzeau and A.Bezerianos are currently co-supervising a PhD student together, but have never worked together with A.Serna. This PhD topic is an opportunity to foster new collaborations within partners of the PEPR.

Description de la proposition de doctorat (3 pages max)

Context: The importance of collaborative distance learning was particularly highlighted by the COVID-19 crisis. To limit the spread of the virus, most countries adopted a containment strategy in which the population was invited to stay at home. Most activities, including meetings, school and university classes, were conducted remotely, using videoconferencing tools (e.g. Zoom, Microsoft Teams, Jitsy). Beyond the COVID-19 crisis, in the context of education, remote learning is important in situations where in-person access to professors or teaching environments may be hard, for example when students may have special mobility needs, or when material (e.g., expensive lab equipments) may not be enough to accommodate multiple students.

While remote colleagues or students doing distance learning are able to adapt their work in remote settings, simple videoconferencing tools are hindering communication and collaboration, and even cause fatigue after intensive use (referred to in the media as “Zoom fatigue”) [1]. A recent report by the European Commission also showed that with these tools, the social aspect of learning is not taken into account, which hampers collaboration and leads to a greater workload for students in particular, as well as boredom, anxiety, frustration and anger [7].

Virtual reality (VR) is a promising solution to this problem, enabling people working together, for example students conducting group work, to share a 3D space in which they can directly manipulate virtual objects and use gestures to communicate. In particular, VR could aid in practical work that is essential in higher education or other problem-solving situations, require active participation and may involve specialised equipment that is difficult to obtain to practise at home. Prior work [12] has shown that *in-person* collaborative learning has social, psychological, academic, and assessment benefits. Nevertheless, it is unclear if these results also apply to learning environments and problem-solving in VR. And whether the measures used in the past to assess collaborative learning can be easily applied in VR settings or other immersive environments.

Objectives: The goal of this thesis is to study and develop real-time measures for assessing collaborative coupling in immersive environments. By processing the detailed data these technologies provide (e.g. communication, interaction logs, gaze), we can track how collaboration evolves over time. We focus on education and collaborative problem-solving tasks, an important aspect of practical activities, recently emphasized in large-scale assessments like PISA. Such measures will allow us to, then, assess the impact immersive technologies, like VR, have on how people collaborate.

State of the Art: Measuring how effectively people collaborate allows us to improve collaboration in a more systematic way [19]. Additionally, in an increasingly technology-driven world, it helps us understand how technology affects both the collaboration process and its outcomes [6]. Many measures exist to assess collaboration quality. In their review, Roberts et al. [17] identified more than 220 approaches. Most rely on self-reported methods, such as interviews [15] or questionnaires (e.g. Social Presence [3]; groupware usability [8]). While these self-reports are relatively easy to administer and cost-effective, they can be difficult to compare and do not allow for continuous tracking of collaboration over time. Another popular approach is to rely on expert observers who count, record, and model collaborative behavior. For instance, Pinelle et al. [16] proposed a task-analysis model for groupware, while Gutwin and Greenberg [10] introduced a framework to conceptualize workspace awareness—the knowledge each collaborator has of the others' activities. Although such observational methods can offer deeper insights, they are costly because they require expert involvement and tend to be highly context-dependent.

A final category of measures relies on automated data, collected in real time during collaborative situations. These measures not only help us understand how people collaborate—similar to the approaches mentioned previously—but also allow us to quantify how individuals coordinate their actions over time, offering a temporal perspective on collaboration. This level of coordination is often referred to as “coupling,” a key concept in collaboration according to Olson and Olson [15], along with common ground, collaboration readiness, and collaboration technology readiness.

Communication is one of the most widely used proxies for assessing coupling, with research often examining the frequency, content, and sequential flow of conversations [17]. Although frequency is the simplest to track, it has not been strongly linked to team outcomes [14]. Instead, analyzing content and flow provides deeper insights into communication quality, but this added analysis complexity means it is rarely employed. In some contexts, researchers have also used physical proximity between participants to infer collaborative coupling, as demonstrated by Jakobsen and Hornbæk [11]. However, this approach is limited to settings where participants can move freely within the shared workspace, such as when working in front of a wall display.

Overall, these measures aim to quantify interactions among collaborators. According to Cooke et al. [4], these interactions embody "team interactive cognition," in which team members cognitively coordinate through their exchanges. Some measures take a more holistic approach to capturing these interactions, such as CAST (Coordinated Awareness of Situation by Teams) proposed by Gorman et al. [9], which calculates the ratio of coordinated perception and action among team members when specific events occur. More recently, Stanton et al. [20] introduced EAST (Event Analysis of Systemic Teamwork), a social network analysis applied to three networks—social, task, and information—during team activities. Although both methods quantify the degree of interaction and coordination among collaborators, they cannot be computed in real time.

Building on these existing approaches, this thesis aims to define a set of measures that leverage real-time data from collaborative tasks to assess collaborative coupling as it unfolds. We will first focus on immersive technologies, as they enable the collection of a broad range of high-fidelity data in real time, thus supporting more robust assessments of collaborative behavior. We also choose to focus on the educational context, a domain that has been studying collaboration, and particularly collaborative learning and its benefits [12], for many years, but focusing mainly on outcomes and learning experiences, and less on the temporal evolution of coordination [23]. Within this educational context, we will initially concentrate on collaborative problem-solving tasks. These tasks are especially relevant given their recent inclusion in large-scale international assessments like PISA.

Research Questions: The thesis will address the following research questions:
RQ1: What are the measures of collaboration used in education science, problem-solving and computer supported collaborative work (CSCW) that are relevant in the context of learning and problem-solving using VR and other immersive environments?
RQ2: How can real-time data be leveraged to reliably assess and quantify collaborative coupling in educational settings?
RQ3: How these measures correlate with traditional measures in education like outcomes and learning experience?

Theoretical Fundation: Collaboration is widely studied in the field of Education. Collaborative learning is defined as a situation in which two or more people learn or attempt to learn something together [5]. In his definition, Dillenbourg insists on the importance of the monitoring and regulation of interactions, the sharing of goals, and the division of labour. Regarding collaborative problem-solving activities, Roschelle and Teasley [18] define collaboration as "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem". For the authors, collaborative problem-solving consists of two concurrent activities: solving the problem together and building a shared knowledge structure that integrates goals; descriptions of the current problem state; awareness of available problem-solving actions; associations that relate goals, features of the current problem state, and available actions. Social interactions occurring during the activity are aimed to construct and maintain this shared knowledge. The authors propose a framework for analysing collaboration based on conversation analysis. Building upon this model and other prior research, Sun et al. [21] propose a general model for collaborative problem-solving assessment consisting in several facets (constructing shared knowledge, negotiation/coordination, and maintaining team function). These facets can inform the analysis of real-time data.

Approach and Methods: The thesis will be divided into the following steps and methodologies:

- *Step1:* One of the challenges, but also novel aspects of this thesis, is that it attempts to consolidate methods from different domains (cscw, education, problem-solving). Thus the first step will be to do a systematic state-of-the-art report on various measures available to characterize collaboration across these fields. We will base this on the work done by Tong et al. [22] on F-Formationand Basille et al. [2] on communication modalities, two PhD students supervised by Serna. This is in and of itself a scientific contribution (*RQ1*)
- *Step2:* Establish a protocol for measuring collaboration as part of a problem-solving task, including the most promising measures identified in Step1. A major challenge in this step is to decide which of these (pre-established) measures are sensitive enough to capture differences in the VR environment. This will require several controlled user studies to isolate the impact and sensitivity of the measures. We will use a VR environment and a task developed by Le Meudec, a current PhD student of Prouzeau and Bezerianos [13].
- *Step 3:* Validate the protocol and measures in realistic use context. Here the measures will be used in two realistic use-cases, where students engage in complex problem-solving learning tasks in VR. We have identified one main use case: Optics practical activities with existing collaborations with professors in this domain that have agreed to integrate our study as part of their classes.

Evaluation: As explained above, we will evaluate our contributions first in controlled experiments, and then in a real use case with optics practical activities.

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Nature de la collaboration numérique (1 page max)

In this thesis, we will focus on collaborative problem-solving using immersive technology (mainly Virtual Reality in our case). The nature of the collaboration can be defined as such:

- Functions: Because we are focusing on problem-solving tasks, the collaborative process will involve multiple mechanisms, including communication across various modalities (e.g., verbal and gestural). Since our use case emphasizes hands-on educational activities, we also want to examine scenarios where learners must jointly manipulate shared objects, as in an optics lab—an interaction that necessitates a high level of coordination.
- Type: We will focus on synchronous collaboration
- Time scale: We will focus on a time scale of hours, as the type of activities we take as a use case are practical activities that usually last 3 to 4 hours.
- Group size: We will work with small groups of participants. In our control studies, we will probably focus on dyads. We may try to increase this size to three or four.
- Space: Because this research focuses on VR, most studies will place participants in the same physical space but unable to see one another, effectively simulating a remote setting. We will also conduct studies in which participants are truly remote. Finally, we may evaluate our measures in a non-VR scenario where participants are co-located in the same room.

Contribution à la collaboration numérique : Résultats attendus et impact (1 page max)

Methodological Contribution: Our primary contribution will be developing a methodology for assessing how small groups collaborate on collaborative problem-solving tasks. This involves creating a systematic set of measures that capture real-time, fine-grained interactions, ranging from communication patterns to coordination behaviors, and validate this set in control studies but also in the field. By integrating temporal data and context-specific indicators, these measures aim to offer researchers and practitioners a more complex understanding of collaborative processes compared to more traditional, outcome-focused methods. The scope of this thesis will only be collaborative problem-solving, but the use of our measures could be generalised to other situations, that could be close problem-solving like in control centres or for crisis management, or quite different like collaborative planning. Of course, they should be validated in these specific contexts.

Empirical Contribution: In addition to our methodological contribution, we will offer an empirical contribution through our focus on the use of VR in educational settings. By studying how immersive environments affect coordination, communication, and shared problem-solving strategies, we seek to explore both the strengths and limitations of VR-based collaboration. In practical terms, the findings will help educators and instructional designers make evidence-based decisions about integrating immersive technologies into the classroom. More broadly, they will reveal how technology-rich environments impact the development of collaborative learning skills, key competencies in today's increasingly interconnected world.

Positionnement dans le programme eNSEMBLE (½ page max)

We believe our project aligns strongly with PC 5 (TRANSVERSE – Aspects transverses à la collaboration), particularly Theme 1: “Méthodes et outils pour mesurer l’impact de la collaboration.” The core objective of this PhD is to develop novel methods for quantifying collaboration within educational activities, capturing both the real-time dynamics of team interactions. By focusing on immersive technologies, our work will also evaluate the potential risks and benefits of these tools—addressing the theme’s call for comprehensive impact assessments of a specific technology and consider both positive and negative outcomes for learners.

We also believe that our project aligns with PC 1 (CATS – Espaces de Collaboration / Collaboration à travers des espaces hétérogènes) as it mainly focuses on collaboration using immersive technologies and aims at proposing measures for synchronous collaboration.