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Collaborative learning in mobile settings: conceptual framework and design of an innovative device to augment flat visual representations

Sebastian Simon

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THÈSE DE DOCTORAT

DE
LE MANS UNIVERSITÉ

SOUS LE SEAU DE
LA COMUE ANGERS – LE MANS

ÉCOLE DOCTORALE N° 641
*Mathématiques et Sciences et Technologies
de l'Information et de la Communication*
Spécialité : *Informatique*

Par

Sebastian SIMON

**Collaborative Learning in Mobile Settings : Conceptual Framework
and Design of an Innovative Device to Augment Flat Visual Repre-
sentations**

Thèse présentée et soutenue à Laval, le 05/11/2024

Unité de recherche : Laboratoire d'Informatique de l'Université du Mans (LIUM)

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INTRODUCTION

Scientific Background

LIUM Laboratory

This PhD dissertation has been carried out within the IEIAH team (*Ingénierie des Environnements Informatiques pour l'Apprentissage Humain*) of the LIUM laboratory (*Laboratoire d'Informatique de l'Université du Mans*), operating at two locations: Le Mans and Laval (France). Since its inception, LIUM has focused on two primary research areas: Technology-Enhanced Learning (TEL) and Language and Speech Technology (LST).

The core scientific endeavor of the TEL team centers on establishing foundational frameworks for the development and engineering of TEL systems. The team activities are organized around these central objectives along three main axes:

1. **Design, operationalization, and adaptation of pedagogical situations:** This dimension emphasizes the integration of educators and instructors into the design process of TEL systems, aiming to create tailored learning environments.
2. **Modeling the observation of usage tracks and their analysis:** This facet delves into the analysis of learning scenarios, leveraging data from teachers and students within TEL systems.
3. **Advanced and collaborative interactions for learning:** The focus here lies in exploring innovative learning interactions, enabled by recent developments in technology, such as interactive tables, mixed and virtual reality, and tangible interfaces, particularly within the context of Serious Games.

The research presented in this dissertation aligns closely with the third dimension, as it addresses the challenge of facilitating collaborative learning within contextualized environments.

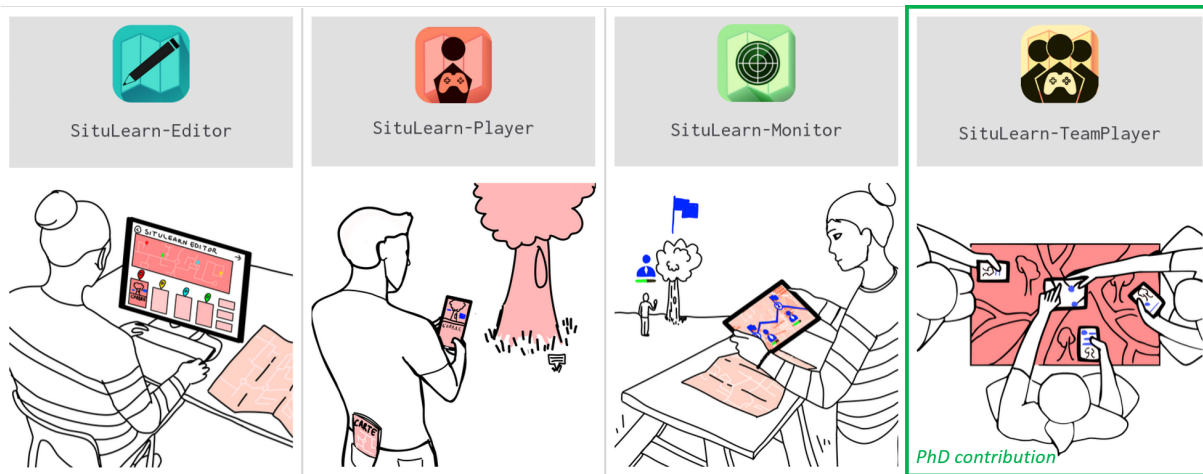


Figure 1: The four components of SituLearn

Project context

Coherent with the third axis of research, this thesis is part of the [ANR JCJC SituLearn project](#) ("*Enrichir l'apprentissage situé avec des jeux collaboratifs et de la réalité mixte*"). The SituLearn project aims to help teachers enrich their educational field trips with mobile applications. The models and tools proposed apply to all subjects taught that profit from learning in the field (History, Botany, Geology, etc.) - from kindergarten to professional training. The project is supervised by Iza Marfisi and has been developed in a Design-Based Research approach with ten pilot teachers. The project proposes four interconnected tools (Figure 1):

SituLearn-Editor is an authoring tool that allows teachers to create mobile applications for educational field trips without programming skills. This software is therefore dedicated to teachers but also to museum mediators and other professions where enhanced situated experiences can be of benefit. The editor features personalized maps, information sheets and geo-located activities such as questions or statements (taking notes, photos and audio recording) with support for in- and outside settings, as well as a large panel of parameters to adapt the activity to its context. Furthermore, the creator can implement scaffolding and set up game mechanics, such as a timer and score system. It also allows teachers to download a report of the field trip, and in particular, to collect the answers to questions and statements from students to use them during debriefing sessions in class.

SituLearn-Player allows students to play the scenarios designed by their teachers with the editor. The application runs as a hybrid web application with offline support in

the learner’s web browser and is thus phone and tablet agnostic. The application allows the user to document their experience with photos, voice recordings and notes.

SituLearn-Monitor is a tool for educators or supervisors to follow the activity of players engaged in the designed scenario during the field trip. Educators can monitor both progress and position and can contact players through the application to provide scaffolding or assistance.

SituLearn-TeamPlayer is planned as a mobile application, with an augmented reality module, to augment available surfaces such as paper maps. The objective is to support collaboration between learners in a way large interactive tabletops do, but through mobile devices. This is the part of the SituLearn project this PhD contributes to. As we will show in this manuscript, the novelty of SituLearn-TeamPlayer leads to complexity: An initial research and development phase to overcome the technological difficulties to create such a workspace is required. On the other hand, research on the aptness of this type of interaction for collaborative learning has to be conducted. This PhD thesis will also propose theoretical contributions related to collaboration features and tools in general.

These four tool applications are built on the SituLearn game model (Figure 2). This model provides the necessary abstraction for different game variants (treasure hunt, interactive walk or activity hub) of possible field trips as well as the possibility to collectively or individually play geo-located scenarios. Figure 2 shows the model with its field-trip specific concepts (POI, Map, Evaluation methods). It also includes concepts of collaborative learning such as teams, collaborative games and milestones, that are placeholders for the results of this PhD.

Research Domain

The overarching goal of SituLearn and the IEIAH team at LIUM is to enhance learning with technology. Technology Enhanced Learning (TEL), by name, is a cross-domain field of education, computer science and engineering. The Higher Education Funding Council for England (HEFCE) defines TEL as “Enhancing learning and teaching through the use of technology” (Palmer 2009), identifying three levels of potential advantages through TEL:

1. Efficiency: reduce required resources of existing processes
2. Enhancement: improve existing outcomes and processes

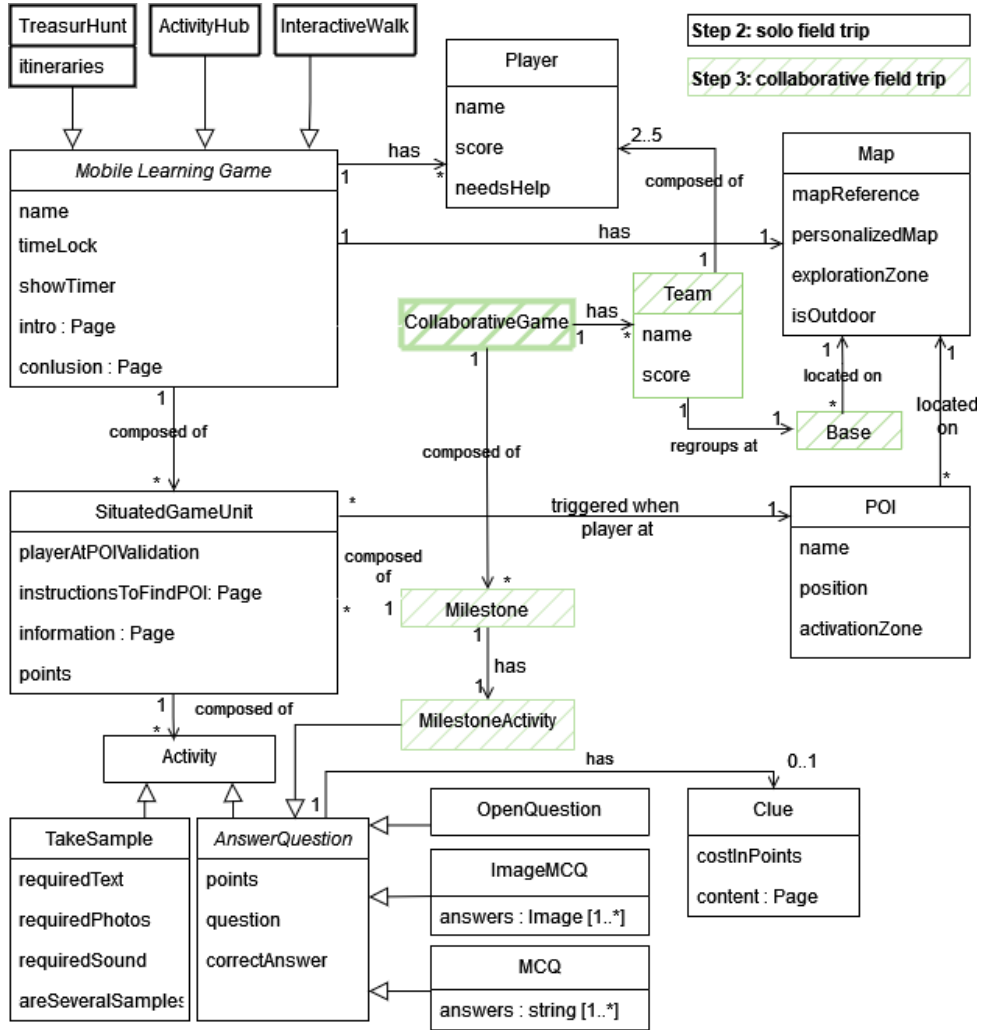


Figure 2: SituLearn model. In green: the model's collaborative elements

3. Transformation: change existing processes

Findings however suggest that educators have a tendency to replicate previous activities, implemented through traditional means (Blin and Munro 2008) and that successful adoption and use leading to enhancement is a complex endeavor requiring a comprehensive research and implementation approach (Q. Liu *et al.* 2020). The term itself is therefore criticized by scholars for implying that technology improves educational activities (Kirkwood and Price 2014). Consequently, it has become a primary objective to demonstrate the added value of technology in education. This, in turn, has resulted in extensive studies in the field of learning analytics to measure the previously mentioned enhancement through technology (*ibid.*). In terms of methodology, TEL studies often deploy an iterative Design-Based Research (DBR) approach, well suited to test novel technology and evaluate it against traditional solutions (Bower 2017).

Not only is this dissertation situated at the crossroads of education and computer science, its collaborative aspect places it in the realm of Computer Supported Collaborative Learning (CSCL), a subfield of TEL. The CSCL research community, similarly diverse to TEL, with researchers of many different backgrounds (Psychology, Sociology, Computer Science, Pedagogy etc.) has vowed to support and study the mode of collaborative learning through technology. The complementary complexity of collaboration makes it a particularly challenging field since collaboration itself is still subject to extensive research.

Finally, the requirement for mobility and the use of collaboration in situated settings, simultaneously stimulating situated learning, places this work in the field of mobile CSCL (mCSCL), concerned with enabling collaborative learning in mobile settings. MCSCL has emerged in the early 2000s with the widespread availability of mobile devices such as PDAs and connectivity such as Bluetooth®, Wifi and GSM (Zurita *et al.* 2001). As we will see in this dissertation, the mobile setting adds additional constraints to the design of collaborative software and hardware. Figure 3 summarized the nested domains of this thesis.

Epistemology

The inherent goals of CSCL, the **analysis** and **improvement** of collaborative learning, cannot be achieved by purely descriptive or correlational approaches or, as Stahl and Hakkarainen (2021) put it, the “former positivist conceptions of theory and of science”. Lave and Wenger (1991) depict learning as “involv[ing] the whole person; it implies not

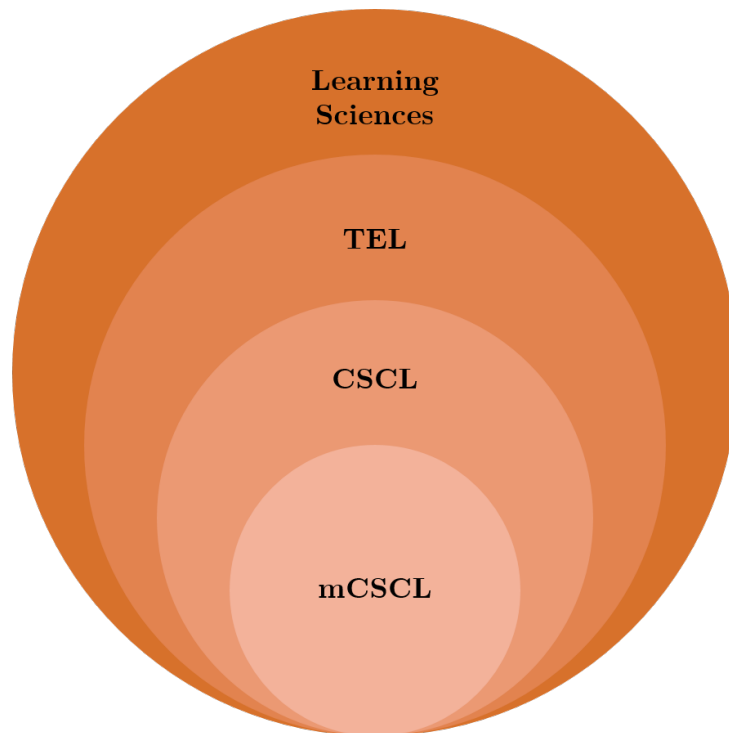


Figure 3: This PhD's research domains

only a relation to specific activities, but a relation to social communities [...] activities, tasks, functions, and understandings do not exist in isolation; they are part of broader systems of relations in which they have meaning.” Holistic understanding of learning and collaborative learning, in particular, call for methods that Glennan *et al.* (2022) situate within the research perspective of the “New Mechanism” movement. This epistemic conception aims to identify the mechanisms of phenomena through the use of a variety of theories such as system theory or complex systems. CSCL, in nature, draws upon such methods. Models in CSCL adhere to the representation thesis (*ibid.*) in that they are “inevitably partial, abstract, idealized and plural”. Stahl and Hakkarainen (2021) add: “Today, the goal of a theory of CSCL is a controversial moving target, not an established canon of universally accepted principles.”

CSCL also relates to the Discovery Pluralism Thesis in that “The diversity of kinds of mechanisms requires and explains the diversity of tools, strategies and heuristics for mechanism discovery.” This is particularly salient in the variety of methods (qualitative, quantitative and mixed methods) and environments (lab experiments, into-the-wild studies etc.) used and accepted in the field of CSCL.

Research Method

TEL, tied to its objective of refuting or verifying the beneficial use of technology in education, had to develop an adequate research method due to the variety of uncontrolled variables in typical study contexts. **Design-Based Research (DBR)** is the predominant method in TEL. The predecessor term “Design experiments” emerged during the early 90s (Brown 1992). Baumgartner *et al.* (2003) describe DBR as follows:

"First, the central goals of designing learning environments and developing theories or “prototheories” of learning are intertwined. Second, development and research take place through continuous cycles of design, enactment, analysis, and redesign. Third, research on designs must lead to sharable theories that help communicate relevant implications to practitioners and other educational designers. Fourth, research must account for how designs function in authentic settings. It must not only document success or failure but also focus on interactions that refine our understanding of the learning issues involved. Fifth, the development of such accounts relies on methods that can document and connect processes of enactment to outcomes of interest."

The authors further explain that DBR consists of simultaneously building and refining frameworks and theories as solutions get progressively refined. This makes it particularly well suited for the use in CSCL, combining two concepts (collaboration and learning) still actively evolving around experimental results.

Another challenge of Technology Enhanced Learning (and, by extension of CSCL) is its intricate process of testing in authentic situations with learners and teachers. The latter oftentimes tend to replicate previous behaviors with new affordances and may encounter difficulties embracing new patterns. The various obstacles of little improvement through new technology due to educator’s lack of flexibility in changing previous behavioral patterns has more recently led to a pragmatic implementation of the DBR method. This PI-DBR (short for Pragmatic Implementation) relies on the inclusion of educators in the conception of technology itself. The educator’s input is crucial before (in-class observations), during (collaboration on educational activities and technological affordances) and after (debriefing and sharing of results) in every cycle of this DBR approach, recently presented by Marfisi-Schottman (2023). Integrating educators in the development approach assures firstly that the tool is convenient and addresses educators needs and secondly introduces educators to the required change in behavioral patterns.

Research Questions

The context of this PhD, presented above, naturally provides an overarching, research problem: **how to support mediated collaborative learning in a mobile setup through the means of technology?**

Previous research has shown that collaborative learning seems to benefit from large interactive workspaces for groups (Mateescu *et al.* 2019). Interactive tabletops have emerged during the last 20 years as the device of choice for studies on collocated collaborative learning. Indeed, their large interactive screens lower the cognitive load for access of virtual elements otherwise hidden in smaller screen configuration requiring additional interactions (such as gestures) to make them visible on the screen. In addition, these devices do not obstruct or limit the vision of group members (as VR headsets or wall mounted displays do). They also provide the possibility to work in parallel in a shared space. However, these devices are not portable and have seen little adoption in classrooms due to their high cost and little available software.

There have been various attempts to overcome these disadvantages. For example, Brudy *et al.* (2018) have investigated the possibility of a static shared, mobile device (e.g. a tablet) and complementary individual mobile devices, reporting improved sense- and decision making during a collaborative trip planning task, due to the presence of a shared device. Jetter *et al.* (2017) tested another approach: the flexible use of multiple tablets to create a common interactive space by aligning them next to each other, but no benefits were reported for this configuration.

The question about the number of individual screens for successful collaboration has been addressed by Plank *et al.* (2017) who concluded that the ideal number is not higher than one device per person.

Similarly, Zagermann *et al.* (2016) conducted a study to determine the optimal device size for collaboration. Results indicate an optimum of a smaller shared device, since smaller screens seem to draw less attention when not in use and thus increase awareness among group members compared to a tabletop device. In our context, smaller screens also have the advantage of being easier to transport for mobile educational settings such as field trips. However, Zagermann's study evaluated an information retrieval task, thus not relying on extensive manipulation of collaborative artefacts (as for example in a collaborative brainstorming activity). Participants also worked in dyads and had additional, traditional media (pen and paper) at their disposal.

It thus seems reasonable to believe that a small number of compact devices can offer collaboration support comparable to that of a larger tabletop device. In turn, the restricted screen size and the added artificial interaction (gestures) for the navigation of virtual space adds to the cognitive load during a group session. Exploring a virtual space with gestures (e.g. zoom and pinch) not rooted in physical space, rather than a direct physical mapping of virtual information, requires training and adds cognitive load (Oviatt 2006).

To reduce the latter (training requirement), alternative, more authentic interactions can reduce cognitive load linked to interaction and thus support collaboration around a tablet better than current interaction types. We hypothesize that interactions, that are similar to natural interactions within the physical space, reduce cognitive load and consequently enhance collaboration.

A promising interaction type is the dynamic peephole interaction. Interactions of this type make use of the device's orientation and position to display virtual information accordingly. Those interactions make it possible to map virtual information and functionalities to locations in space (for example star-gazing applications). In their study, Kaufmann and Ahlström (2013) observed positive memory effects of participants using a projector phone whose rotation allowed to explore a virtual map that was revealed by the projector beam when moved (like a flashlight revealing physical space in a dark room). In the experiment, the entire map could not be displayed at once. Based on these results, we believe that providing a static background with information linked to the dynamic overlay, for example through an interaction on a horizontal tablet put onto a static support, such as a printed map, could further support the cognitive effort of recalling the position of virtual information.

In this thesis, we therefore investigated, developed and tested an alternative configuration in the form of a paper-tablet hybrid. Our first research question is **RQ1: Does an augmented reality interaction consisting of a mobile device, being placed and moved across a static surface, constitute an improved collaborative learning support? If this is the case, how does it influence collaboration?**

At its core, this is an engineering problem, since we search a tool to fulfill the requirements of mediated collaborative learning and mobility. As it turns out, not only does the hardware to experiment such an interaction not exist, but in addition, the design of collaborative software is still an active area of CACL research (Simon *et al.* 2024c). S. D. Scott *et al.* (2003) noticed that “few existing technologies provide the rich, fluid interactions that exist during collaboration involving paper-based media”. Morris *et al.*

(2006) highlight the high impact on collaboration that slight alterations of user interface design can have:

"Overall, our experiences in designing and evaluating educational tabletop groupware indicate that relatively small UI variations, such as the modality or privacy of feedback, the layout of objects on the shared surface, or the presence of explicit awareness information, can produce observable impacts on students' team work styles."

Given high sensitivity of groups to user interface design and collaborative tool features, it would be highly helpful for developers of tools intended to support collaboration, to have, firstly, a database with all software and hardware features that support collaboration depending on activity and context, and secondly, information about how individual features impact collaborative processes in order to design appropriate groupware. Beyond the endeavor of identifying, not only a list of such features, but moreover successfully linking them to aspects of collaboration, software features do not exist in isolation. When we mention context, we also include co-present software features. It might be possible that the combination of collaborative features within a tool impacts negatively or positively collaboration as a whole or part of it. Studies on collaborative tools typically investigate the impact of the tool as a whole on collaboration. Only recently have studies focused on distinguished aspects of collaboration (e.g. territoriality or types of awareness) and developed and tested collaborative features (Simon *et al.* 2022a). To the best of our knowledge, this problem has not been addressed in literature. We therefore have identified **RQ2: Does a comprehensive list of collaborative tool features exist? What is their impact on collaboration? How do different combinations of features affect collaboration?**

This research question however implies that there is a homogenous understanding within the community of research what collaboration is (what do these tool "features" support or enhance?). As we considered in the subsection "Research domain" and what will be the subject of the following part of this dissertation, a global definition of collaboration does not exist and makes for the third, conceptual dimension of this work, incidentally the title of a key paper of the domain: "what do you mean by collaborative learning?" (P. Dillenbourg 2000) What we argue for, is a common conceptual vision of collaboration that can support design and analysis. As stated before, a vision of CSCL is subject to change and evolution. However, even a common vision that changes can help inform analysis and design and by consequence enhance comparability. Our third research

question therefore is **RQ3: Given the multi-domain nature of CSCL, does a common vision of it exist? If not, can we establish common ground from existing literature?**

Motivation

Collaboration is considered one of the four central skills for successful societies in the 21st century (González-Pérez and Ramírez-Montoya 2022), besides creativity, critical thinking and communication. As we will demonstrate in this work, successful collaboration requires the use of all of these skills. It can thus be considered a composite skill, which, when mastered, equips individuals with the abilities not only to thrive in modern societies, but also to contribute to the progress of the society they live in.

While this PhD thesis is mainly concerned with learning through collaboration as opposed to learning collaborative skills, research has shown a positive effect from collaborative learning activities to the development of collaborative skills (Roseth *et al.* 2008a). For both cases of collaboration, research into which conditions lead to successful collaboration is of central interest in order to sustain or teach collaboration.

Initial observations during the project SituLearn coincide with literature in that it is not enough to put people into groups for collaboration to occur on its own (P. Dillenbourg 2000). Among the conditions favoring collaboration, is the complexity of the given problem or task. If the task or problem may be addressed by an individual member of the group, collaborative cognitive load theory (P. A. Kirschner *et al.* 2018) stipulates that members of a group might not engage in the additional cognitive load required for successful collaboration (group coordination, conflict and resource management). In the context of learning activities, the learning activity is thus either sufficiently ill-structured or should feature positive interdependence by design (for example by distributing task relevant tools or information among group members, inducing the necessity to collaborate). Furthermore, the presence of collaborative skills, values and knowledge among members of the group is an additional condition for successful collaboration. Learning activities might provide scaffolding for missing collaborative skills within the group (X. Wang and Mu 2017).

Finally, tools can be considered another condition for collaboration. Considering and integrating technology into collaborative environments, both per its ubiquity and its affordances (shaping the way its users think and act) is a major challenge. Today, individuals

and groups act within a continuum of virtual and actual reality. Augmented reality is currently an affordable and practical compromise between both poles that seems to provide the means (accessibility, technological maturity) to support mobile collaborative learning best.

However, it is still unclear which of the many shapes and affordances tools can take constitutes a collaborative optimum for a given context. Finding collaborative optima is of paramount importance to contribute to a better understanding of the many aspects of collaboration as a whole and increasing existing knowledge about collaborative processes.

Contributions

To answer research question RQ1, we initially researched technology enabling a horizontal, dynamic peephole interaction. These technologies were analyzed according to a set of technical requirements (e.g. precision, delay) and constraints in the educational sector (e.g. affordability, availability, mobility and reparability). The successful design of two mechanical prototypes allowed for two field studies with 32 and 12 middle school students and to capture usage data from visitors of a science fare.

Research question RQ2 has been addressed through a meta-analysis of 49 selected studies. In this work we identified 20 recurrent features present in tools developed for the analysis of collaboration. We successfully mapped these features depending on the studies' overlapping results to a three dimensional vector space that represents the main collaboration processes: Participation, Awareness and Coordination.

This vector space is the result of a preceding, conceptual analysis on common concepts of collaboration in literature (RQ3). We combined different frameworks on collaboration into a joined framework in order to establish a common vision on the previously mentioned role of tool features on the different aspects of collaboration. We further confronted this framework with recent works of CSCL which led to a second iteration of a joined collaborative framework. This second version is a proposition to the CSCL community to establish and maintain a common conception of the whole domain and the quality of cross-validated interconnections between different collaborative processes. It also allows to model the relationships between CSCL and CSCW and is meant as a guide and documentation tool for experimentations, integrating different frameworks for collaborative analytics.

Thesis Structure

This dissertation is structured by the many questions that have led our way through the last two and a half years and which can be grouped under the three research questions presented in this chapter. Figure 4 sums up the chronology of question areas (Hardware, Software and Theory) and the underlying logic dependencies (yellow arrows). We initially dedicated effort to the development of a prototype through which a horizontal dynamic peephole interaction could be tested. Since an interaction with a device happens through software, we investigated the issue of collaborative software features. Both software and hardware have to function in combination to support collaboration or collaborative learning. As such, the fundamental question for the development of both is what it is we want to support in collaboration. Without a clear and detailed vision of those concepts, one can neither design nor evaluate the efficiency of a dedicated system. Consequently, the structure of this dissertation follows the logical dependencies and is organized in five parts.

To begin with, **the first part will present the conceptual underpinnings** of our work (RQ3). In this part, a first chapter examines the question of a common definition for CSCL, before establishing a detailed vision of collaboration and associated concepts (collaborative learning, CSCL etc.) through a joined, multistage *conceptual framework*.

The second part focuses on collaborative features in collaborative tools to highlight their impact on collaboration (RQ2). To this end, the first chapter of this second part will discuss collaborative features and the second chapter will establish the link between collaborative processes identified in the first part and the features of chapter one of this second part in a *mapping* between the concepts and collaborative features.

The third part is focused on the development of collaborative hardware and interactional affordances for collaboration (RQ1). There, we first present existing CSCL hardware. We then evaluate different interaction types for collaborative situated learning before detailing the applied method and requirements for hardware to enable the previously identified interaction. A technological state of the art is presented in the fourth chapter. Chapter five of part three will present the design and development of the *prototypes* used in the field studies, subject to part four of this dissertation. **The fourth part presents the two studies** led with these prototypes. In each of the two chapters (one for each study), we will present the experimental setup, the activity design, the method, the analysis and discuss the results. Finally, **the fifth part presents conclusions and draws perspectives** from the presented work of this thesis. According to our structure,

we will present perspectives for the conceptual, software and the hardware contributions and evaluate if the initial question has been satisfied, concluding on how this work can inform the Situlearn model.

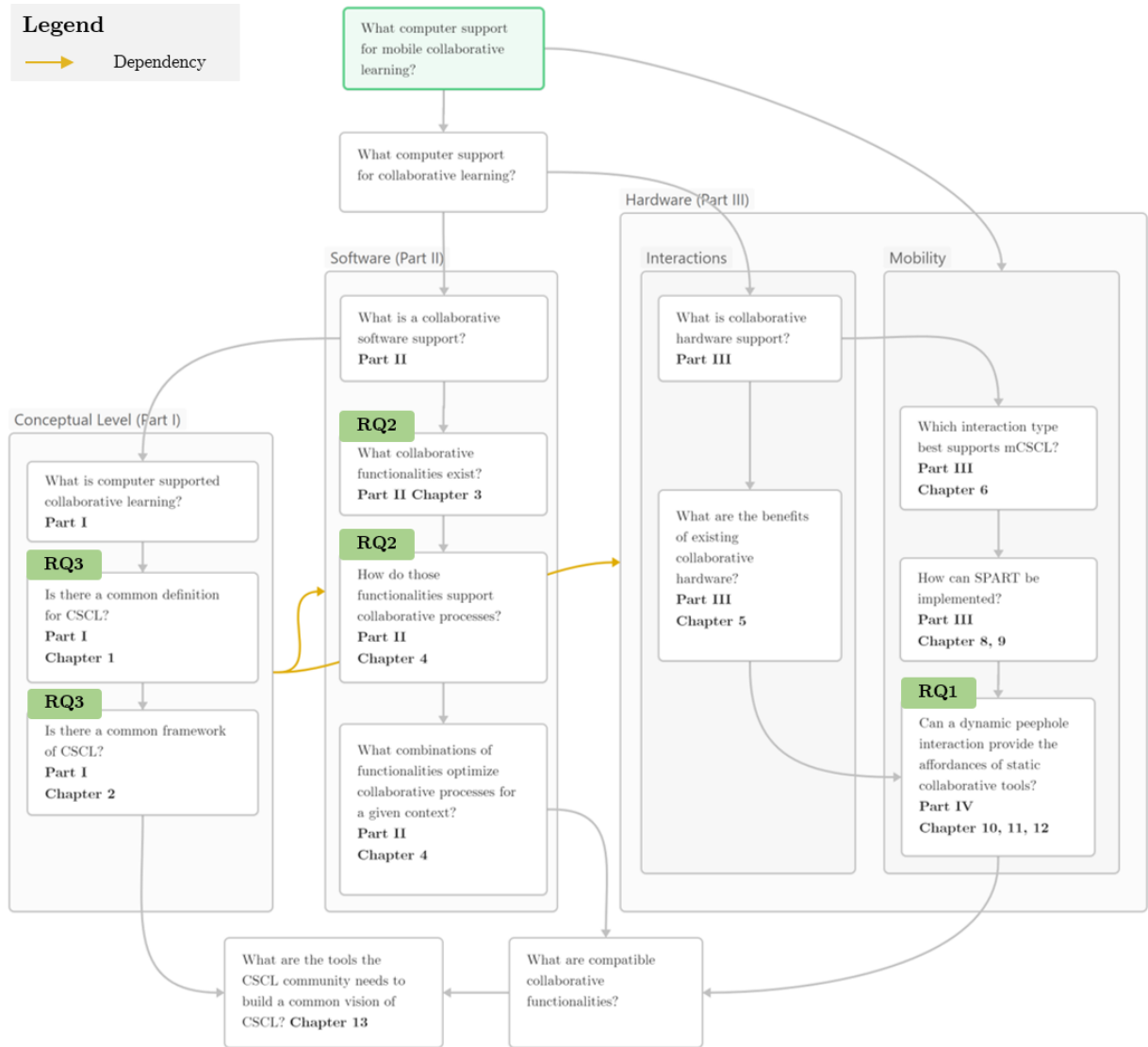


Figure 4: Dissertation structure inspired by the different research (sub)questions. Yellow arrows highlight dependencies, grey arrows sequence)

PART I

Concepts and Theories

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CONTEXT

Almost 30 years ago, Roschelle and S. D. Teasley (1995a) defined collaboration as “a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem”. While this definition still holds today, it is, at the time of writing, surrounded by a variety of collaborative activity designs, tools and environments, each inspired by different definitions, frameworks and theories from different fields (Stahl 2021a).

CSCL - A challenging domain

The **variety of theories and frameworks on collaboration** can be attributed to the multidisciplinary nature of Computer-Supported Collaborative Learning (CSCL). Indeed, CSCL is a domain at the crossroads of psychology, learning sciences, computer science, sociology, linguistics, anthropology and communications (Hmelo-Silver and Jeong 2021).

This variety of research work has become **difficult to review** (Vatrapu 2011) since it offers many different visions, each represented by multiple frameworks (Scardamalia and Bereiter (1994), Linn (2003), Suthers (2003) etc.). This, in turn, has produced a heterogeneous landscape of research. For instance, as will demonstrate this part of the dissertation, the many different ways of viewing CSCL, lead to results of collaborative learning in scholar search engines (e.g. google scholar) that may not depict topics actually related to Collaborative Learning (Challco *et al.* 2014).

Another problem is that the variety of conceptual visions has come along with a **variety of analytic frameworks**. These offer methods to analyze collaboration and collaborative learning. As Watzlawick and Weakland (2004) pointed out in their work *About Interaction*, theory informs method. 20 years after a key work by P. Dillenbourg (2000) asked the question “What do you mean by collaboration?”, to provide a more detailed vision of what collaboration means on the conceptual level, “What do you mean by collaboration Analytics?” by Martinez-Maldonado *et al.* (2021) attempts to bring clarity within the variety of analytics frameworks. In our opinion, this is an issue that persists today and is crucial to conduct replicable and comparable experiments, further elucidating the

mechanics of collaboration. The variability in methods and analytics frameworks adds to recent works by A. F. Wise and Schwarz (2017), Rummel (2018) and Damsa *et al.* (2024) questioning conceptual underpinnings and showing the still pressing issue of conceptual variety in the field.

Even without the variety of analytical frameworks, TEL (and by consequence CSCL) **already has an inherent problem of reproducibility**: Tools and software are oftentimes one of a kind and sample sizes small, due to the required cooperation with teachers for into-the-wild studies and groups as the unit of analysis. The missing common conceptual ground (and resulting, different methods) further add to this dilemma.

CSCL – a learning community?

Another reason for the variety of models might also be the fact that, at the time of writing, while studying collaborative learning (CL), the research community itself can be modeled as a learning community, but not as a collaborative learning community (whose main issue is to maintain a common understanding).

In **collaborative learning**, learners have to agree on a common vision of a typically ill-defined or wicked problem through communication (Clark 1996), itself based in a shared language. If the CSCL community was indeed a collaborative learning community, the produced frameworks, definitions and theories would be revisions of the same artefacts of common ground over time. While the current part of this dissertation will reveal that this is the case to some extent, it will also show that representations of collaboration have emerged in parallel and show incompatibilities.

What differentiates a researcher from a learner is the ability to be at the origin of knowledge that might challenge or add to their conceptual representation of computer-assisted collaborative learning in a symbiotic circle of theory and practice. However, there is no unique synchronized cycle among the community. Many researchers work in parallel in different fields with different perceptions of computer support, collaborative learning, collaboration and learning (Cress *et al.* 2021). Collaboration has also been identified as a complex skill and concept and hence has yielded a number of sub-concepts with dedicated research (for example research on the concept of social presence). Therefore, it is all the more urgent to **engage in a collaborative action of conceptual convergence** for the community, to master a transition from a learning, to a collaborative learning community, as pointed out by Rummel (2018). Efforts to reunite CSCL knowledge are

underway (Cress *et al.* 2021): the community’s latest edition of a comprehensive handbook has been published in 2021. The urgency of conceptual consolidation has been recognized by leading researchers (A. F. Wise and Schwarz 2017) questioning if “one framework to rule them all” is an adequate response to the problem. We argue instead for a duality of an overarching framework in conjunction with existing specialized frameworks. During the challenge of conceptual convergence, the community can draw from its own research on successful collaboration. Initially, this however requires a process of communication to negotiate different points of view into a common vision of CSCL.

Contributions

In order for successful communication to take place between individuals, the vocabulary has to be agreed on. Definitions are linguistic corner stones and key to successful communication. When a group first attempts to build common ground, differences in definitions to concepts have to be sorted out or discussed before successful knowledge building can happen. To this end, we will start by **comparing existing definitions** and evaluating their respective quality to ensure a common language for an improved collaboration. Although definitions are a good starting point, they constitute a compromise of conciseness and accuracy (Landau 1984) and more importantly, are supposed to capture the essence of the concept. Yet, if collaboration is still under active investigation and not fully understood, capturing its essence presents a particular challenge. Nevertheless, taking on the work of comparing existing definitions even with the outlook of obtaining a vague definition, is in our opinion worthwhile, since it provides a language for establishing common ground. Since the common ground is a detailed and shared vision of collaboration, the definition can still be modified afterwards. This is the second contribution we propose in this part. Not only will we investigate common language on key concepts of CSCL, but we will attempt to **provide a first joint framework** based on the joint definitions and literature on collaboration as a scaffolding, dynamic artefact for this intended community collaboration. By dynamic we mean that the framework itself should not be considered a final tool, but rather a proposition for community wide discussion and proposals for modification and extension. Frameworks can be considered extensions of definitions (Jabareen 2009).

While definitions elucidate a concept by referencing a small number of other linguistic concepts, frameworks do so without the restriction of conciseness. Frameworks address the

inherent fuzziness of meaning in definitions which originates from the fact that a single definition relies on the user's interpretation of the concepts it references and the rule of **conciseness** a definition has to adhere to. In many ways, a framework faces similar challenges to a dictionary in that it is aimed at conveying meaning of symbols through linking together different concepts. Landau (1984) for instance states that definitions in dictionaries rely on the use of other concepts to convey meaning, and hence create a network of knowledge, a vision common in domains such as semiotics, psychology and linguistics (Fellbaum 2010). Jabareen (2009) in turn defines conceptual frameworks as "a network, or "a plane," of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena". Other indicators for the shared, underlying structure of both frameworks and dictionaries are criteria for the quality of definitions, for instance the absence of direct circular relationships (if the definition is defined through another which in turn is defined by the former).

Structure

The methods of framework and definition building in this dissertation are borrowed from lexicography and semantic theory. In chapter 1, we identify and establish a common definition for CSCL by decomposition: Since CSCL is a composite term of Computer Support, Collaborative learning, Collaboration and Learning, we firstly establish definitions of these terms before combining them into a definition of CSCL. Then, in chapter 2, we elaborate on these definitions to propose a framework on collaboration that provides a more detailed vision of the collaborative process, its input conditions and output. We propose a first, core version of this framework, before elaborating it into an extended version comprising analytic and design frameworks, interconnections and further elaborating both in- and output. Finally, we will conclude on the findings of those two chapters and compare the compatibility between the initially developed definitions and the framework. Since the definitions have been developed prior to the frameworks, we aim to compare them to the proposed framework to see if they are compatible, and if not, investigate why, in order to provide a coherent global vision of collaboration at different levels of detail. The following chapters (and their respective publications in conferences such as ECTEL and CSCL/ISLS) are meant as conversation starters for joint visions of definitions and frameworks in the CSCL community.

Related Publications

Simon, S., Marfisi-Schottman, I., George, S. (2022, September). Towards A Comprehensive Framework for Situated Collaborative Learning Tools. In *Proceedings of the Doctoral Consortium of the 17th European Conference on Technology Enhanced Learning (ECTEL)*. Toulouse, France, 72-80.

Simon, S., Marfisi-Schottman, I., George, S. (2023, June). Towards Linking Tool Functionalities to Processes of Collaborative Learning. In *ISLS (International Society of the Learning Sciences) annual meeting International Conference of Computer Supported Collaborative Learning (CSCL)*, p. 205-208, 2023. Montréal, Canada, p. 205-208.

Simon, S., Marfisi-Schottman, I., George, S. (2024, June). Towards a Framework to Link Them All - A Provocation in the Ongoing Debate on Collaborative Learning. In *Proceedings of the 17th International Conference on Computer-Supported Collaborative Learning-CSCL 2024, ISLS 2024*. Buffalo, United States, p. 123-130.

CSCL DEFINITIONS

Definitions are essential linguistic building blocks for communication (Rogoff 2003). Definitions thus are necessary for building common ground, a key feature of successful collaboration. Furthermore, as research can be considered a large scale collaborative endeavor, consisting of contributions from different researchers, **common definitions are essential to scientific coherence.**

However, a common definition of the CSCL field does not exist (yet). Indeed, in his recent work “Advancing a CSCL Vision”, Stahl (2021a) admits that “Previous attempts to circumscribe the field of CSCL have faltered; the target is so nebulous, controversial, disjointed, multi-dimensional and agonistic”. This is due to multiple reasons, one of which is that CSCL is a field at the crossings of many disciplines (psychology, learning sciences, computer science, sociology, linguistics, anthropology and communications (Hmelo-Silver and Jeong 2021)). Different fields deploy different vocabulary and one of the many difficulties the CSCL community faces, is that its limits are not clearly defined. In this chapter, we examine whether (and if so, how) a common definition can be established for the field of CSCL. We emphasize that such a definition constitutes a contribution towards a shared understanding rather than an attempt to find a one-size-fits-all solution.

In earlier works, Stahl *et al.* (2006) offer the following definition of CSCL: “Studying how people can learn together with the help of computers.” It shows the composite nature of CSCL, being defined by its key concepts of Computer Support and Collaborative Learning. While Stahl’s definition of CSCL seems not to be challenged by other authors at the time of writing (e.g. Järvelä *et al.* (2023)), in lexicographic terms, it constitutes a recursive definition that relies on definitions of its two components: Computer Support and Collaborative Learning. Collaborative Learning, in turn, is a composite concept, combining Collaboration and Learning. Furthermore, definitions on learning depend on its underlying paradigm. Likewise, collaboration is a complex concept that, to this day, is under active investigation by a variety of research communities. Consequently, collaborative learning inherits the variety of visions on its concepts and passes its linguistic fuzziness to the domain definition of CSCL.

In an attempt to provide better conceptual clarity, we examine definitions of these key

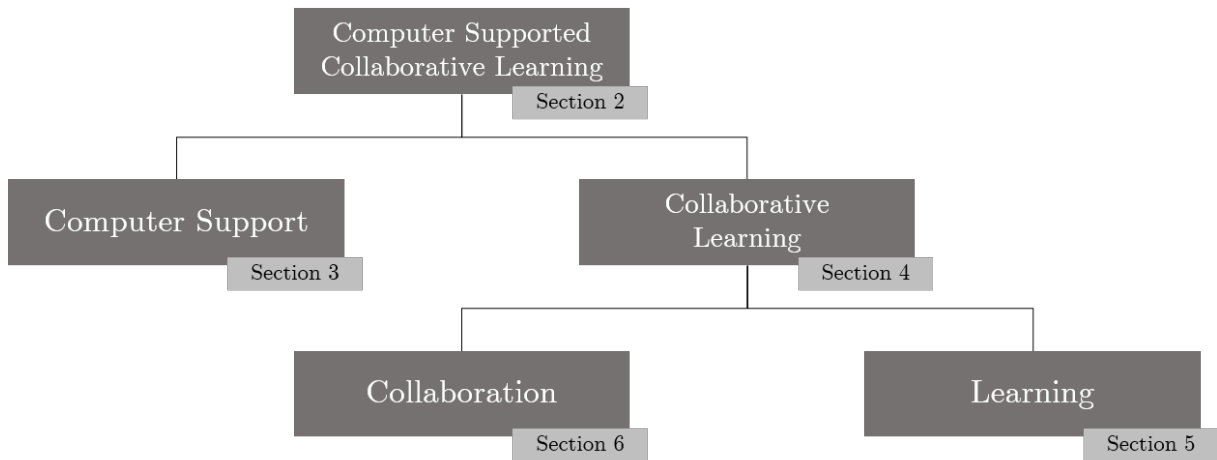


Figure 1.1: The structure of this chapter, organized by the decomposition of CSCL.

concepts in this chapter. Firstly, we establish whether a **common** definition exists, before establishing whether it is a **recursive** definition. If this is the case, we further decompose. Once at an atomic level (e.g. concepts like collaboration, learning and computer support), if the available definitions differ fundamentally, we attempt to **combine** common elements into a cohesive definition. In the event of a larger number of varying definitions, we use the approach of **defining vocabulary**. This method, used by lexicographers, consists in **taking the most frequently used concepts** to determine a common definition (Hurford *et al.* 2007).

To ensure the quality of the chosen definitions, we evaluate each definition against a set of criteria we will present in section 1.1. The subsequent sections are dedicated to definitions for each of the concepts found in CSCL (itself including): section 1.2 details further Stahl (2021b)’s attempt to circumscribe the domain, section 1.3 discusses definitions of Computer Support (CS) and section 1.4 explores definitions of Collaborative Learning (CL). We further attempt to find definitions for the last composite concepts, Learning and Collaboration, in section 1.5 and 1.6 (as illustrated in figure 1.1).

Having followed a logic of decomposition, in the final, concluding section, we will attempt to reconstruct clear, composite definitions for CL and CSCL.

1.1 Assessing Definitions

Establishing definitions is a regular process among lexicographers. Accordingly, we adhere to best practices and use criteria that have evolved for the creation of dictionaries to assess

the results of this chapter qualitatively:

1. **Accuracy** The definition should describe the concept without ambiguity or error through genus and differentia.
2. **Circularity** The definition should not have direct or transitive circularity with only one intermediary concept.
3. **Conciseness** The definition should avoid unnecessary elaboration or repetition.
4. **Consistency** The definition should be coherent with established terminology and concepts within the relevant field.
5. **Relevance** The definition should be relevant to the context in which it is used, addressing the specific needs or questions of the audience.
6. **Accessibility** It should be comprehensible to the target audience.

The Oxford Dictionary (2024a) defines a definition as “A precise statement of the essential nature of a thing; a statement or form of words by which anything is defined.” Landau (1984) defines “essence”, in that it should capture the main features of the concept all while being simple to understand. **Conciseness** (“the quality of being short and clear, and expressing what needs to be said without unnecessary words” - Cambridge Dictionary (2024a)) seems to capture this description well and will thus be a criterion for definitions. Since statements are part of communication, definitions have a public and a goal, the latter being to accurately and concisely describe a concept (Hurford *et al.* 2007). Furthermore, the public of a definition exists in a context (in which and to whom it is **relevant**). Thus, assumptions can be made about what the public is aware of and what not (Suchman 2002) to reduce the length of the definition (conciseness), all while maintaining **accessibility** and **accuracy**. To implement the latter, Aristotle assesses definitions through Genus and Differentia of the Definiendum (the word to be defined). Genus refers to the class the concept belongs to (e.g. a human is a mammal) and Difference to how the concept is different from others of the same class (Landau 1984). In addition, **circularity** should be avoided in a definition (both direct circularity, that is to use the Definiendum within the definition and transitive circularity, e.g. "Man: The opposite of a woman" and "Woman: The opposite of a man"). A final criterion is **consistency**: Definitions are part of a linguistic model, referencing each other mutually. For linguistic models to coherently mirror reality, those models must show consistency

with the reality they depict, and so they must exhibit linguistic coherence “for it is the model that we can communicate and validate through our experiences and this is what we refer to by talking about creating common ground” (Stahl 2021b).

1.2 Computer Supported Collaborative Learning

As outlined in the introduction, CSCL is a composite concept. Having questioned his earlier definition (Stahl *et al.* 2006), Stahl, admitting to the absence of a common CSCL definition (Stahl 2021b), argues that, what can be established at the current time, is a vision based on a prototype example that often comes to mind, “like a robin is a prototypical bird”. The prototypical design he proposes is the following:

"The vision of CSCL advanced here is that students working in small groups can productively incorporate collaborative learning centrally in their schooling and in their intellectual development, taking advantage of appropriate forms of computer support."

This prototype essentially states that CSCL is the productive combination of computer support and collaborative learning. While this definition is easy to comprehend, the details of what a productive combination of the two are, is the subject of an ongoing research debate, as neither has a clear definition.

1.3 Computer Support

The definition of **Computer Support**, by the Oxford Dictionary (2024b), describes “The availability of tools in the form of electronic devices for storing and processing data, typically in binary form, according to instructions given to it in a variable program”. It is not clear, from such a definition, what is supported by the electronic devices, and in the context of CSCL, this may vary between support for collaborative processes (e.g. organization tools, voting mechanisms, scaffolding etc.) or the alleviation of activity complexity through interaction types or activity related tools (cognitive scaffolding, such as worked examples in a math task for example). Another problem with Stahl’s vision, (“students working in **small groups** can productively incorporate collaborative learning centrally in their schooling and in their intellectual development, taking advantage of appropriate forms of computer support”), is its restriction to small groups. This typically excludes

larger groups, such as communities collaboratively writing Wikipedia articles for example. Yet, this can be considered collaborative learning (of a topic) with computer support (Stockleben *et al.* 2017). In his paper *Computer-supported collaborative learning: The Basics*, Pierre Dillenbourg and F. Fischer (2007) associate Computer Support not only to the scope of the **users** being students or **learners**, but also to **educators** to produce coherent group activities for collaborative learning. Moreover, Dillenbourg highlights the role of the computer support to gather data and usage traces for researchers to better understand the conditions that lead to successful collaboration. In addition, the Computer part in CS encompasses a wide variety of devices. So much so that the term “ubiquitous computing” has declined rapidly in usage, as computing in 2024 has become ubiquitous (in the sense of Mark Weisers vision of computing in the 21st century). The great variety of tool support adds to the complexity researchers face studying topics like CSCL. At the time of writing, the definition of CS has not been narrowed down and thus contributes to the domain’s complexity. What can be observed instead, are dynamics to collaboratively embrace the complexity of computer support through the bias of frameworks to describe computer support. For instance, Soller *et al.* (2005) distinguish between regulation and structuring roles of CS in collaborative activities as follows:

1. “Structuring approaches aim to create favorable conditions for learning by designing or scripting the situation before the interaction begins”
2. “Regulation approaches support collaboration by taking actions once the interaction has begun.”

Moreover, CS variety has more recently inspired a proposal for a common taxonomy of computer support to be considered during experimentation in order to establish a common standard and increase comparability (Rummel 2018).

1.3.1 Proposal of a Joint Definition of Computer Support

Given our previous elaborations on both support variety and support user type, we propose the following definition for Computer Support in the CSCL context:

Computer Support describes any electronic device destined to support learners work in collaborative learning setups or support educators and researchers to create, monitor, or analyze the former.

1.3.2 Evaluation

We evaluate this definition against the criteria defined in section 1.1:

1. Accuracy: It specifies genus (electronic devices) and differentiates itself from other devices in its use for collaborative learning.
2. Circularity: It does not reference itself.
3. Conciseness: It depicts the reality and variety of purposes and devices of computer support, in the field of CSCL.
4. Consistency: It is based on an existing definition and works of the domain.
5. Relevance: In our context it is necessary to clearly define sub concepts like computer support and collaboration to bring linguistic sharpness to the concept of CSCL itself.
6. Accessibility: The use of common terms makes this definition understandable to the general audience.

1.4 Collaborative Learning

Now that we have provided a definition for Computer Support, we attempt to find a common definition for the remaining concept of CSCL: Collaborative Learning. This turns out to be more complex since opinions on the essence of this concept diverge and historically, different pedagogical currents have emerged: cooperative and collaborative learning.

1.4.1 Two Currents: Cooperative and Collaborative Learning

As George (2001) notes, the term *collaborative learning* can be traced back to British educators such as Mason (1972) or James (1968) while cooperative learning has emerged on the American continent with researchers such as D. W. Johnson and R. T. Johnson (1974). In *Building Bridges Between Cooperative And Collaborative Learning*, Matthews *et al.* (1995) differentiates both practices along three dimensions:

1. Teacher's guidance: Cooperative Learning requires supervision by the teacher.
2. Roles: Cooperative Learning preserves the authority of the teacher to guide students through structured activities and students take predefined roles in activities,

whereas, in collaborative learning, negotiating those roles is part of the learning process Smith (1979).

3. Social skills: Collaborative learning requires existing (collaborative) skills, while cooperative learning aims to transmit them.

Other points of view exist: Gamson (1994) considers Collaborative Learning an extension of Cooperative learning: “Collaborative learning is always cooperative, but takes students one step further: to a point where they must confront the issue of power and authority implicit in any form of learning, but usually ignored”.

1.4.2 The Learning in Collaborative Learning

Another question of interest is, what is learnt during either cooperative or collaborative learning: Bruffee (1993) argues that “Collaborative Learning gives students practice in working together when the stakes are relatively low, so that they can work effectively together later when the stakes are high”. This point of view considers collaborative learning the learning of collaboration. Meanwhile, studies have indeed shown that depending on context, collaboration can have benefits for the learning process (Lou *et al.* (2001); Roseth *et al.* (2008b); Slavin (1980); Springer *et al.* (1999)). Other than the distinction between the two concepts and if cooperative learning is actually part of CSCL (as we argue, given the existence of a whole subfield called “collaborative scripting” to alleviate the complexity of collaboration to facilitate the learning of content), the question what kind of elements either one includes (and which are relevant for a definition), is still subject to research. However, attempts on definitions have emerged since the constitution of the field of CSCL: Roschelle and S. D. Teasley (1995b) consider Collaborative learning a process where “two or more individuals work together to understand a problem, complete a task, or create a product”. It often involves shared goals, mutual interdependence, and coordinated efforts to achieve common objectives.”. While this definition does not only detail the goal structure, mentions coordination and is also suitable as a definition for the concept of collaboration itself, the difference to cooperative learning or collaborative work is absent.

In 2006 Pierre Dillenbourg and Traum (2006) present a definition on the type of interactions and activities within Collaborative learning: “two or more people learn or attempt to learn something together. It can involve joint problem-solving, discussions, debates, or any other form of interaction aimed at deepening understanding or mastering

a subject”. The focus in this definition is clearly content learning, against Bruffee (1993)’s vision of collaborative learning as the learning of collaboration. Stahl *et al.* (2006) propose the following definition: “Collaborative learning involves the mutual engagement of participants in coordinated efforts to solve a problem together, often through dialogue, negotiation, and shared responsibility for learning”. While Dillenbourg considers discussions and debates as a vehicle for collaborative learning, Stahl treats them as components of collaboration with one goal only, finding a solution to a problem together, learning being a natural “byproduct” of the process (following socio-constructivist visions such as Lave and Wenger (1991)).

In recent works, Stahl (2021b) defines collaborative learning as knowledge construction and collective meaning-making, highlighting two collaborative key processes of collaborative learning. In summary, not only are there different visions of collaborative learning within the domain, cooperative and collaborative learning seem to have merged or are used interchangeably. In this dissertation, we will refer to the historical collaborative learning (as in the learning of collaborative skills, values and knowledge) as the learning of collaboration. By doing so, the concept of collaborative learning, as used presently, including both learning of collaboration and cooperative learning can be used and when required, the distinction can be made. Bruffee (1993)’s argument for collaborative learning situations providing students with a playground to develop their collaborative skills holds true. It seems that the concept of collaborative learning, as used presently, can impact both, collaborative skills and learning outcomes, even before we consider eventual social outcomes originating in the rich social interactions that collaboration provides (Mateescu *et al.* 2019). This means, that while conceptually, both concepts, can be clearly distinguished, in practice both components (as well as social and product outcomes) can be considered a continuum in the design of a collaborative activities. Thus, to further detail the now explicit concept of collaborative learning, in the next two sections, we dive into its composite concepts: learning and collaboration.

1.5 Learning

The scientific domain concerned with the analysis of learning, has evolved from Cognitive Psychology and Artificial Intelligence in the 1970s and 80s. The goal of understanding what learning is and how it works, however, dates back to the beginning of the former of those two disciplines which in turn originates in the early 1800s (Dunlosky and Rawson

2019). Thus, the key concept of learning has undergone multiple evolutions and is present today in different learning theories.

1.5.1 Piaget and Vygotsky’s vision of learning

A milestone in the theoretical conceptions of learning was the theory of Jean Piaget, published in the first half of the 20th century, positing “different stages of cognitive development, culminating in abstract thinking” and explaining learning as two processes of assimilation and accommodation in *La Construction du Réel chez l’Enfant* (Piaget 1937).

Later, Vygotsky (1978) influenced conceptions of learning, describing it as social construct, a perception built on most notably by Lave and Wenger (1991) considering learning a social byproduct as the legitimate peripheral participation in a community of practice. Consequently, today, “Learning science considers learning to be a transformation of patterns of participation in sociotechnical systems and communities of practice” (Dunlosky and Rawson 2019). This definition includes another aspect of the latest learning theory: connectivism. Connectivism is a theoretical framework that acknowledges the role of technology in learning. It is not limited to interactions in the physical space, but also includes interactions, both synchronous and asynchronous through media such as social networks, wikis etc. It can be considered an extension of socio-constructivism in that it emphasizes the role of interactions but extends the type of possible interactions. It is not in sharp opposition to the theory of social-constructivism.

In contrast, Piaget’s individualistic view on learning and Vygotsky’s focus on social interactions do not seem compatible initially. The incompatibility between the two scholars seems to originate in the question where meaning-making occurs. For it is meaning that only exists in the mind of the individual for Piaget. Meaning in Vygotsky’s metaphor comes to exist in an inter-individual social context. One might argue that, while it is not enough to just “add social context onto Piaget’s individualistic approach” (Rogoff 1990), it might just be that meaning both exists between and within individual minds. A simple object such as a hammer can have meaning to the individual by its possibility to enter a nail into a piece of wood. The meaning within a group of individuals in turn for the same object might differ in that the members of the group have other usages in mind. At this stage, meaning is still individual, even if it may stem from social practice. Upon communication, inter-individual meaning making occurs and the group might pool their knowledge about individual usages to enrich their group vision. Members might argue if such or such use

case is possible or not with a hammer or if the tool is adequate. Piaget realized that this type of scenario closely matches his idea of the individual process of “accomodation” and “emphasized cooperation as the ideal form of social interaction, promoting development because he believed that the social relations involved in cooperation are the same as the logical relations that children construct in regard to the physical world.” Rogoff (*ibid.*).

"Cooperation itself constitutes a system of co-operations: putting in correspondence (which is an operation) the operations of one partner with those of the others, uniting (which is another operation) the acquisition of one partner with that of others, etc.; and in case of conflicts, raising the contradictions (which presupposes an operational process) or above all differentiating the different points of view and introducing between them a reciprocity (which is an operational transformation)." (Piaget 1937)

In the previous example, we notice that meaning exists both in the individual situation and within the group. While both points of view seem contradictory at first, the extended notion or differentiation of meaning provides the possibility to create a joined perception of learning. Inversely, scholars of collaborative learning such as Stahl, have introduced the idea that a group and an individual might not be fundamentally differently functioning entities: Stahl observed that an individual can also be considered a collection of systems that need to collaborate in order to produce meaning: the visual system, the frontal cortex etc. Interactions in groups might just help researchers better understand how individual learning works by analyzing group communication.

Another difference between the two researchers is the role of a “more capable learner”. While Piaget argues for equality among learners within the social context, Vygotsky stresses the role of a more capable person for learning to take place. In the context of cognitive development in children, Vygotsky seems to attribute this role to an adult, where Piaget notes the problem of **hierarchy** that may result from such a difference between two learners. While hierarchy has been shown to present a problem in learning (Pierre Dillenbourg 1999), hierarchy is no necessary consequence of a bigger skillset or more knowledge, but it requires the more knowledgeable or skillful person to acknowledge the importance of equality and take into account social norms that typically may postulate hierarchy between two people, for example of different age or social status (e.g. teacher and student (Paulo 2017)). Rogoff notes that the two points of view might be appropriate for different situations:

"The resolution of cognitive conflict may be necessary for a child to discard an existing belief to consider one that is qualitatively different, to achieve a Piagetian shift in perspective, as when children realize that the quantity of water does not change when it is poured into a container of another shape. And interaction with an expert may be necessary to provide practice in skills and access to information required to become proficient with culturally developed tools for thinking."

1.5.2 Knowledge Building

While Piaget and Vygotsky describe the process of learning and where it takes place, the outcome implicitly is a product that is acquired by the learners. Today, a still prominent textbook definition of learning is “the process of *gaining* knowledge or experience” (Cambridge Dictionary 2024b) . Keith Sawyer and John Dunlosky (2019) oppose this vision by stating “that teaching and learning cannot be accurately and completely understood when considered to be a transmission of information” and define learning in the *Cambridge Handbook of Cognition and Education* (Dunlosky and Rawson 2019) “to be **a transformation of patterns of participation in sociotechnical systems and communities of practice.**”, further defining “patterns of participation” as “symbolic interactions between group members (. . .), roles and responsibilities of each member” and “interactions with **technological artifacts.**”

The definition of a *community of practice* is given as “a set of individuals who share a common culture, a knowledge of those practices characteristic of a culture, an understanding of the value of those practices to the culture, and a knowledge of how to participate appropriately in these practices”, *technological artifacts* that “refer to a wide range of modernity and sophistication. Such artifacts include paper and pencil, books and printing, video, continuing with today’s technologies.” and the *sociotechnical system* as “people and technological artifacts, closely intertwined”. With contemporary technologies, it becomes increasingly difficult to consider human–computer interaction as a “human user” employing a “tool” to accomplish a task. This conceptualization implies a clear distinction between the user and the tool. But with augmented reality, for example, the line between user and tool blurs. The line between interacting with a tool and interacting with another person also blurs – for example, if those other people are avatars in a virtual reality world. This last definition is particularly useful to include individuals and groups in the definition of learning. This **critique of the “transmission” metaphor**, as coined by Stahl,

is shared by Lachman (1997) who describe learning as “a relatively permanent change in behavior brought about by practice or experience”. In contrast, De Houwer *et al.* (2013) argue in their work *What is learning? On the nature and merits of a functional definition of learning* for learning as an “ontogenetic adaptation”. De Houwer *et al.* challenge the argument of patterns of participation and behavior by arguing that latent learning effects do not require changes in behavior to occur, defying a functional approach to a definition of learning. The argument however does not defy previous definitions completely, it merely criticizes their scope and that changes in behavior might not be a necessary indicator for learning. De Houwer *et al.* note that functional definitions rely on the immediate relationship of cause and consequence (contiguous causal effect) but can explain effects like latent learning by some internal process that overcomes the time delay. In his work he argues against such a definition since internal processes are “very difficult” to verify. This is a central problem of all short term learning studies to evaluate the success of any learning activity and thus is an indicator for a mechanistic definition. While an immediate effect is not sufficient to determine whether learning occurs or not, changes in behavior eventually appear through practice. Albeit the outcome of a learning process might not be immediate, a functional definition still seems of interest. Such a definition also is compatible with Piaget’s vision of acquisition and accommodation, further describing them as sometimes latent processes requiring time before they result in changes of patterns of behavior.

1.5.3 Proposal of a joint Definition of Learning

We therefore propose the following definition that combines the above perceptions and definitions:

Learning is a process of negotiation and assimilation of information into mental representations, resulting in (potentially latent) changes of behavior in socio-technical systems.

The definition does not state whether the process of learning is individual or collective and thus comes with a certain flexibility for where meaning making takes place. The findings in this section will alimnt the investigation of the role of collaboration to support learning in the next section.

1.5.4 Evaluation

Along previously defined criteria, we can evaluate this definition as follows:

1. Accuracy: The definition is the result of a combination of known learning theories with little loss in accuracy in respect to the definitions of their respective authors.
2. Circularity: The definition does not use or make reference to immediate neighboring concepts or itself.
3. Conciseness: Given the complex nature, the definition still fits a single sentence.
4. Consistency: Due to the linear process of negotiating different learning theories, the definition is consistent and compatible with the major intellectual currents.
5. Relevance: The definition is relevant as an attempt to convey joint meaning of the concept of learning.
6. Accessibility: While the concept of socio-technical systems requires further definitions, the definition is still comprehensible for novices in the field, since its composite concepts (social and technical) are commonly known.

1.6 Collaboration

The beginning of modern conceptualization of collaboration is difficult to pinpoint. The works of Mary Parker Follet prominently questioned existing organizational structures in the early 20th century and proposed key concepts such as common goals for workers and managers within companies (Follett 2013).

1.6.1 Collaboration and Cooperation

In *A theory of cooperation and competition*, Deutsch (1949) provided a first distinctive theoretical framework of cooperation, a concept very similar to collaboration. Within his 31 hypothesis to the nature of cooperation, key concepts (that also are an important part of collaboration) are outlined (e.g. positive interdependence). He also highlights the distinctive goal structure of cooperation (as opposed to competition) and defines cooperation as an interdependent structure of goals through a set of logic statements (e.g. “if A, B, C, etc. do not obtain his goal (enter his goal region), X does not obtain his goal. X obtains

his goal only if A, B, C, etc. obtain theirs"). Those statements elaborate a central concept of collaboration, notably **goal interdependence**. This goal structure also allowed **differentiation between cooperation and collaboration** by more recent authors. George (2001), for instance, base their distinction on this goal structure: Collaboration can be distinguished from cooperation in that cooperation provides individual subtasks and -goals that can be parallelized, while a collaborative approach does not assign individuals to sub-tasks and -goals, requiring the group to constantly exchange to resolve each task. The distinctive feature of different goal structures doesn't translate well into the realm of collaborative learning and cooperative learning, as George et Leroux pointed out (since both collaborative and cooperative learning feature common learning activity goals). The unfortunate (or more likely the absence of) naming conventions might explain the problem of finding a common definition for collaboration in particular and for CSCL in general.

Schöttle *et al.* (2014) further compare cooperation and collaboration in the context of lean construction. Beyond the **goal structure** between the two "collective activities", the authors differentiate cooperation and collaboration along the dimensions of **trust** (required for collaboration/not required for cooperation), **the group structure** (less flexible in cooperation and jointly developed in a collaboration), **rewards** (shared in collaboration, separate in cooperation), **planning** (collaboration: jointly as opposed to cooperation) and **leadership** and decision making (concentrated on one person in cooperation vs participative in collaborations). This comparison already features a framework in what both cooperation and collaboration consist, reflected by the resulting definition :

"Collaboration is an inter-organizational relationship with a common vision to create a common project organization with a commonly defined structure and a new and jointly developed project culture, based on trust and transparency; with the goal to jointly maximize the value for the customer by solving problems mutually through interactive processes, which are planned together, and by sharing responsibilities, risk, and rewards among the key participants."

Cooperation, in turn, is defined as

"an inter-organizational relationship among participants of a project, which are not commonly related by vision or mission, resulting in separated project organization with an independent structure, where the project culture is based

Authors/ Concepts	1 System entity	2 Synchrony	3 Effort	4 Objectives	5 Agency	6 Common Ground	7 Pooling Knowledge	8 Outcome	9 Open Communication	10 Trust	11 Mutual respect	12 Responsibility	13 Active Participation	14 Joint Decision Making	15 Problem Complexity	16 Horizontal Hierarchy	17 Complementary Expertise	18 Conflict Resolution	19 Negotiation	20 Joint Rules / Structures	21 Shared Norms	22 Mutual Caring
Appley & Winder 1977	p			cg		cg																
Wood & Gray 1991	p		je		a	su																
Rogalski et al. 1994	a		je	i	a			o														
Roschelle et al. 1995	p		je	sg		cg																
Schrage et al. 1995	p				p	su																
Dillenbourg 1999	s		wt	sg	p/a																	
Thomson et al. 2009	p			i	a																	
Schöttle et al 2014	r		wt	cg	p/a			o														
Friend and Cook 2014	p				a	su																
PISA 2015	p		je		a	cg		s														
Hesse et al 2015	a		je	cg		cg		o														
Cambridge Handbook of Education	i			cg	p																	
Griffiths et al. 2021	p		wt	sg		cg		s														
Alozie 2023	p		je	cg	p			s														
Cambridge Dictionary 2023	s		wt	cg	p																	

Table 1.1: Comparison of definitions of collaboration. Gray: concept present. Letters designate differences in literature - 1p process, 1a: activity, 1s: state, 1i: interaction, 3je: joint effort, 3wt: working together, 4cg: common goal, 5a: agent, 5p: person, 5p/a: person or agent, 6cg: common ground, 6su: shared understanding, 6o: outcome, 6s: solution

on control and coordination to solve problems independently in order to maximize the value of the own organization."

1.6.2 The Many Definitions of Collaboration

Given the rich literature on the subject, we will deploy the method of definition crafting presented in the introduction of this chapter (using the most used terms among all definitions) and assess the result with the previously used criteria. The sources have been chosen to cover a variety of different perspectives, all concerned with providing a comprehensive vision: a dictionary definition, the perspective of transnational organizations such as the OECD, literature reviews and foundational works in collaborative learning and collaborative work.

The different definitions' elements have been grouped and arranged by common **con-**

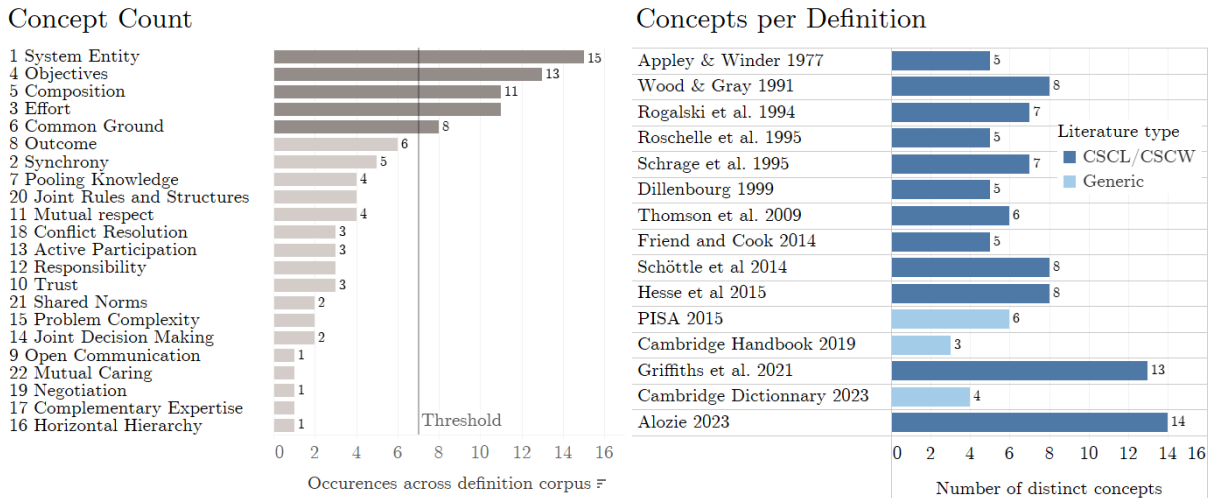


Figure 1.2: Visualization of table 1.1. Left: concepts with more than 50 % occurrences in the definition corpus (dark gray). Right: number of concepts per definition

cepts in table 1.1. In total, 15 definitions have been taken into account. In the next sub-sections, we will discuss retained concepts and differences to finally propose a global definition of collaboration, based on the majority principle: if an entity has at least 8 occurrences across the corpus of definitions and is of similar type, it will be included in the joint definition.

As depicted in table 1.1, the concepts that appear more than 8 times are the system entity of the type “process” -1:p, the notion of effort (3) (considering “working together” -3:wt and “joint effort” -3:je as synonyms), objectives (4) (considering “common goals” -4:cg and “shared goals” -4:sg synonyms), composition (5) (considering “agents” and 5:a “people” -5:p synonyms) and common ground (6) (considering “common ground” -6:cg and “shared understanding” -6:su synonyms). We will describe each of these in detail in the next sections.

Figure 1.2 shows the concepts present in the majority of definitions (left). The right side diagram shows the number of distinct concepts in the definitions. A trend to more concepts per definition seems to occur (especially if we consider domain literature (highlighted in dark blue). Noticeable is also the wide variety of 22 different concepts that appeared in the different definitions.

1. System entity describes the basic structure of the concept of collaboration. The different characterizations of collaboration range from static descriptions such as “relationships” (Schöttle *et al.* 2014) and “state” (Pierre Dillenbourg 1999) to dynamic

entities such as “**process**” and “**activities**” and “**interactions**”. While a process can be considered a series of related activities to reach a new state of a system, a state is a static snapshot of a system. Since research on collaboration has established the multifaceted nature of collaboration, an activity alone seems inadequate. Similarly, Vogel *et al.* (2017) point out the importance of transactive actions which contradicts the vision of a collaborative state anew. As the majority of definitions adopt a process point of view, we adopt this notion for a joint definition.

3. Joint effort and **4. Objectives** are recurrent across definitions. Even authors who do not explicitly include joint effort or “working together” in their definitions, such as Thomson *et al.* (2009), describe collaboration in their work as a process where actors “act or decide on the issues that brought them together”, insinuating a common effort to address the “issues”. The OECD (2015)’s definition does not explicit the common goal, but the “problem” actors try to solve.

5. Composition describes the number and type of actors implied in collaboration. While definitions by Roschelle and S. D. Teasley (1995a), Hesse *et al.* (2015) and Griffiths *et al.* (2021) do not explicitly include the need for more than one entity, their works repeatedly evoke multiple participants in collaborative activities. Therefore, the consensus seems that **two or more entities** are required for collaboration. Concerning its type, neither person or actor has a majority in our corpus of definitions. To this extent and in the light of progress in artificial conversation agents (e.g. large language models), it seems wise to keep the abstract notion of entities.

6. Common ground appeared across 8 out of 15 definitions. In Schrage (1995) it appears as “shared understanding”. The concept describes how groups have to communicate to get “on the same page” concerning the problem at hand. It is, as Stahl (2021b) puts it, an exchange of visions to establish one which is common to the group.

All other concepts did not occur sufficiently often (less than 8 occurrences) and thus will not be discussed here.

1.6.3 Proposal of a Joint Definition of Collaboration

We can now establish the following definition of collaboration:

Collaboration is a set of collective processes (1) in which two or more entities (5) engage in a joint effort (3) towards a common goal (4) by establishing common ground (6).

This definition highlights its affiliation to the class of collective processes (George 2001) and how it can be distinguished from other collective processes such as cooperation (joint effort).

Comparing our definition with table 1.1, we observe that the proposed definition, while sharing the most individual elements with each of the definitions, does not correspond to one of them completely.

1.6.4 Evaluation

We evaluate this definition as follows:

1. Accuracy: The definition has been obtained mainly through the method of defining vocabulary. Consequently, the definition might miss important elements. Since the details of collaboration are under active investigation, this is inevitable and will improve over time. Yet, the definition was presented in a long paper accepted at the ISLS/CSCL annual conference, which constitutes a preliminary approval of its elements.
2. Circularity: The definition does not use or make reference to immediate neighboring concepts or itself.
3. Conciseness: Given the complex nature, the definition still fits a single sentence.
4. Consistency: Since the definition includes foremost elements with high frequency in previous definitions, it is consistent with literature.
5. Relevance: As the definition of learning, this definition is an attempt of a common ground for conceptual exchange on the matter. Interestingly, since the essential components are not known at this point, the definition is of less interest than the framework of collaboration (which we will present in the next chapter); we estimate that through continued CSCL research, the definition will be updated and gain in relevance and accuracy.
6. Accessibility: The definition is comprehensible to novices in the field and uses common vocabulary.

1.6.5 Conclusion on Definitions

In the introduction of this chapter, we established the importance of common language, and by extension, common definitions for finding common ground. We have observed fuzziness in the definitions of CSCL. The strategy we have deployed in this chapter to improve linguistic sharpness, is one of decomposition. We initially defined CS - computer support, and then both C - collaboration and L - learning. We have been able to identify common definitions for each of these concepts, after thoroughly comparing the different perspectives and visions. We can now reversely combine these isolated definitions to provide a clear definition for collaborative learning:

Collaborative Learning is a process of negotiation and assimilation of information into mental representations, resulting in (potentially latent) changes of behavior in socio-technical systems, through a joint effort within a group, towards a common goal through the establishment of common ground.

Compared to one of the often cited CL definitions (Stahl *et al.* (2006): “Collaborative learning involves the mutual engagement of participants in coordinated efforts to solve a problem together, often through dialogue, negotiation, and shared responsibility for learning”), we notice similarities in engagement, common goal (composite definition) and solving a problem together. Not only does our composite definition align with Stahl’s definition, it also mirrors the current usage of “collaborative learning”, including learning of collaboration and cooperative learning: Since collaborative outcomes can be considered collaborative skills, values and knowledge, these outcomes present a subset of the more general learning outcomes which are negotiated and assimilated within socio-technical systems. Instead of separating the two, we consider them inherently intertwined.

On the subject of learning research, Janssen *et al.* (2010) differentiated research on CL as either process-oriented or effect-oriented. Process-oriented research in CL inspects the mechanisms of collaboration whereas effect-oriented research investigates the effect of collaboration on learning. The composite definition presented aligns on those two complementary research approaches by stating that it is through collaboration that learning takes place and in parallel describes the process through which collaboration takes place.

Finally, we can propose our definition of CSCL:

CSCL is the domain of analysis, design and improvement of the process of negotiation and assimilation of information into mental representations, resulting in (potentially latent) changes of behavior in socio-technical systems through a joint effort within a group towards a common goal, through the establishment of common ground assisted by information technology devices.

This definition is a proposition to the identity of the domain. While not perfectly concise, it can serve as an abstract introduction.

In conclusion, this chapter has, through the process of decomposition and consolidation, yielded definitions for the CSCL domain for learning, collaboration, collaborative learning and the field itself. We have noticed remaining uncertainty in the articulation of learning and collaboration in collaborative learning that require further investigation, particularly on the impact of collaboration on learning and its inner workings. To this end, the next chapter will provide a joint framework of collaboration to shed light on these issues.

A FRAMEWORK FOR COLLABORATION

In the previous chapter, we formulated a definition of CSCL based on different perspectives. We noticed a variety of definitions for each notion, particularly around the concept of **collaboration**, themselves deploying varying concepts. This variety stems from the fact that collaboration is still an actively researched and widely used concept. This, in turn, gives us reason to believe that, what is required to improve design and analysis of CSCL experiments, is not only a common definition of collaboration, but a **common framework** to detail which concepts are involved in collaboration and how they interact with each other.

The creation of a common framework is crucial to the future work of the CSCL community, as it enables the research community to identify the key characteristics of collaborative concepts (which in turn can lead to an improved definition of collaboration, CL and CSCL). Such an endeavor requires a coherent, general, vision and converging effort. Currently, the existence of many independent frameworks leads to difficulties in comparison of research, something particularly problematic in the CSCL context of oftentimes small convenience samples and a large number of uncontrolled but potentially dependent variables.

Nevertheless, these diverging frameworks play their part in highlighting specific facets of collaboration and should not simply be absorbed into one monolithic framework “to rule them all” (A. F. Wise and Schwarz (2017), Rummel (2018)). Researchers such as Suchman (2002) argue for “a shift from a view of objective knowledge as a single, asituated, master perspective that bases its claims to objectivity in the closure of controversy, to multiple, located, partial perspectives that find their objective character through ongoing processes of debate”. We view the different existing frameworks as precisely this: Different, partial perspectives on the phenomenon of collaboration, and we view our work as a debate between those different perspectives from which we propose what only can be another partial perspective, but one that emphasizes consensus across those frameworks, attempting to **bridge the existing perspectives** where possible (or highlight, if existent, contradictions across these partial views). Such a particular partial perspective, we argue, can provide a starting point from which the community can build common ground and

hopefully engage in a continuous debate on the subject.

The interest to provide such a framework extends beyond a debate among the CSCL community to define its concepts. A common conceptual stance allows for a better comparability across different studies and fields (CSCL and CSCW for example), provides conceptual underpinnings for new studies and, in return, is to be alimented by the results of those studies to “reframe the locus of objectivity from an established body of knowledge not produced or owned by anyone, to knowledges in dynamic production, reproduction and transformation, for which we are all responsible” (*ibid.*).

In this chapter, we will thus describe two versions of one **joint framework for collaboration**, which we named the **PAC framework** (based on its three main process categories: **Participation, Awareness and Coordination**). The simplified version, called the **Core PAC framework**, is presented in the first section of this chapter. It is a first vision of collaboration we constructed for the analysis of collaborative functionalities across different studies (itself the topic of the next part of this dissertation). It was first presented at the ECTEL conference in 2022 and served later as the basis for the PAC mapping of functionalities to collaborative dimensions which was presented in 2023 at the ISLS/CSCL conference. Furthermore, it provided the conceptual underpinnings to our field studies (which we will discuss in part 4), presented at the CSEDU conference in 2024 .

The **extended version of the PAC framework**, presented in the second section of this chapter, has been developed specifically as a community artifact and proposition to trigger a movement of collaboration and convergence in and beyond the field of CSCL. It is built from and compatible with the first, simplified version of the PAC framework and was extended through a literature analysis of existing frameworks. It was presented at the ISLS/CSCL conference in June 2024 ¹.

Both versions integrate the process-like aspect of collaboration put forward by the many different definitions we have studied in the previous chapter. Both frameworks are a work of comparison and integration of existing frameworks, concepts and links. Therefore, the acceptance by the CSCL community of those frameworks at conferences like ECTEL 2022, ISLS/CSCL 2023 and ISLS/CSCL 2024 gives us hope that it will be adopted by the community. We insist on its generic nature on collaboration, even though it is a perspective from the field of CSCL.

1. Therefore, even if we particularly highlighted our work’s future benefits for the CSCL community, it primarily provided a very real benefit to our own work.

2.1 Core PAC Framework

This section is dedicated to the **core version** of the PAC framework, evolving around the process-like structure of collaboration, identified in the previous chapter. Figure 2.1 provides an overview of this framework. The origin of each concept and their meaning are presented in the next sections.

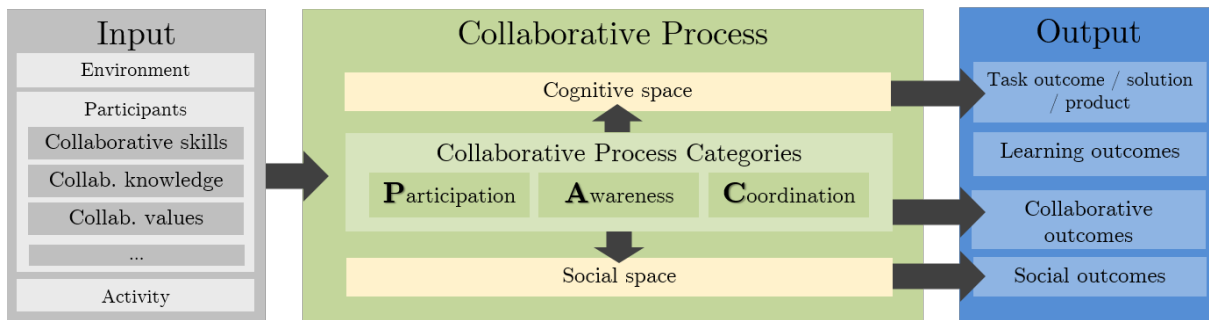


Figure 2.1: The Core PAC Framework

2.1.1 Method

The core PAC framework we propose is the result of a gradual extension from the definitions in the previous chapter, through the inclusion of key CSCL frameworks. The previous analysis of definitions of collaboration has resulted in 9 out of 15 definitions explicitly highlighting collaboration as a process. Consequently, the PAC framework is grounded in standard system theory, defining processes as a triple of input, process and output (W. S. Davis and Yen 2018): Every process, to function, requires either requirements from the environment and/or an artefact on which it operates (input). The output designates the result of the process (figure 2.2 (1)). At the center of the process are the collaborative (sub)-processes.

We defined process categories (2) (Participation/Awareness/Coordination) through a comparison of three key frameworks (Hesse *et al.* (2015), Meier *et al.* (2007) and Mateescu *et al.* (2019)). These processes are complemented (3), (4) by the key notions of cognitive space (Roschelle *et al.* 1995) and social space (Bannon 2006). We further detailed the input and output for the collaborative process (5), (6) through incorporating two other key frameworks P. A. Kirschner *et al.* (2018), D. W. Johnson and R. T. Johnson (2009)). These steps are detailed in the following section, and the result thereafter.

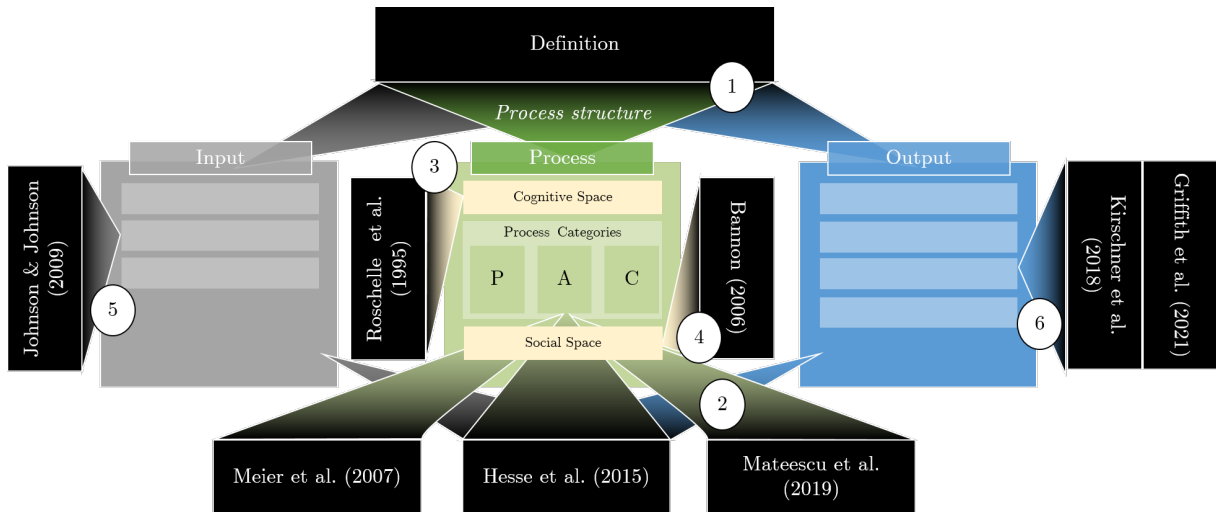


Figure 2.2: The construction of the Core PAC Framework. In black: Works or artefacts used in the design of the process. Numbers represent the sequence of steps.

2.1.2 Building the Core PAC Framework

The Input-Process-Output (IPO) model is a widely used model in system theory and computer science. In his work *The development of Collaboration Theory: Typologies and Systems Approaches*, Williams (2015) concludes that “all frameworks employ the basic systems template categories of inputs-processes-outputs”. Although his work is situated in the domain of administration and public policy, it provides an interesting perspective on collaboration in a domain rarely considered in the field of CSCL and confirms the IPO structure choice for a framework on collaboration (figure 2.2 (1)). In the next subsections, we will present the Process part, then the Input and the Output of the core PAC framework.

Process

In recent years, two categories of frameworks in CSCL have surfaced. The first focuses on collaborative skills, exemplified by Hesse *et al.* (2015) and aims to identify what skills are necessary for students to initiate and maintain successful collaboration. The second is centered around collaborative processes, such as the works of Meier *et al.* (2007), which aim to establish a process-oriented perspective on physical collaboration. As previously mentioned, collaborative learning and the acquisition of collaborative skills are intertwined efforts. Consequently, we leverage insights from both types of frameworks, brought forward by prominent researchers in the domain’s main journal *ijCSCL*, into our joint PAC

framework proposition. Furthermore, insights from Mateescu *et al.* (2019) are included since their systematic and relatively recent work is based on a large corpus of 1491 studies between 1997 and 2019.

In the following paragraphs, we firstly present these contributions separately in order to highlight common aspects before proposing a joint framework drawing on those common features.

Hesse *et al.* (2015) differentiate between cognitive skills and social skills in their framework for the assessment through a three-stage scale of teachable collaborative problem-solving skills. The list of skills proposed is divided into the categories of social skills including participation, perspective taking, and social regulation, whereas the category of cognitive skills revolve around learning and knowledge building, as well as task regulation. Participation is the observable action of engaging in discourse and Hesse *et al.* differentiate between action, interaction, and task completion. Perspective taking is defined as the capacity to comprehend the thoughts and knowledge of others. Social regulation entails the ability of group members to recognize and mitigate biases (e.g., confirmation biases) in order to fully utilize the group's cognitive resources. Task regulation is synonymous with planning and coordination skills. Knowledge building refers to the ability to integrate ideas from collaborators to refine problem representations, plans, and monitoring activities, while learning pertains to the capacity to identify and represent relationships, comprehend cause and effect, and formulate hypotheses based on generalizations.

Meier *et al.* (2007) outlined five dimensions of collaboration in their attempt of assessing the quality of collaborative processes: communication, joint information processing, coordination, interpersonal relationships, and motivation. Communication encompasses activities like *grounding* to build a shared understanding of concepts, while joint information processing involves reaching consensus on decisions and collectively process available information. To achieve this, group members must be aware of each other's knowledge and make use of Transactive Memory Systems (Wegner 1987). Coordination refers to the management of resources and the oversight of critical subtask sequences, while interpersonal relationships, as described by Meier *et al.* (2007), are characterized by the absence of hierarchical structures, where members hold equal status, aligning with Pierre Dillenbourg (1999)'s concept of symmetrical relationships. Finally, motivation encompasses both individual member's drive towards contributions and their commitment to the group task's outcomes.

Mateescu *et al.* (2019) identified five collaborative dimensions in their systematic re-

view on collaborative studies: workspace awareness, verbal and gestural communication, participation, coordination flow, artifact interaction, and level of reasoning. Workspace awareness designates the ability to understand another person’s interactions with the shared workspace, while verbal and gestural communication corresponds to the frequency of assertions, questions, and answers exchanged. Participation refers to the degree of involvement by participants in the problem-solving process, and coordination encompasses strategies for linking or orchestrating individual contributions within a group. Artifact interaction denotes the utilization of any object (e.g. tangible tokens) during collaboration. Finally, Level of reasoning is defined as the level of reasoning observed in or expressed by group members.

The collaborative processes of these three frameworks, can be regrouped under three complementary process categories: Participation, Awareness and Coordination (PAC).

The **Participation** category contains collaboration processes that Meier *et al.* (2007) grouped under communication and Mateescu *et al.* (2019) within verbal and gestural communication, as well as the literal “participation” category itself. Without communication, collaboration cannot function, and thus, every communicative act is participation in collaboration. We widen Hesse *et al.* (2015)’s definition of participation as an “observable action of engaging in discourse” into an observable action of engaging in communication. Indeed, communication can occur through other means than discourse, for example gestural communication, as reflects the category proposed by Mateescu *et al.* We further follow Hesse *et al.* in their distinction of different levels of participative processes along actions, interactions and task completions. This category definition allows us to include processes considered by Mateescu *et al.* as artefact interaction. Examples of participative collaborative processes are grounding (the process of building a common vision by adapting individual knowledge to the other person’s level of understanding), dialogue management, building on existing ideas, challenging arguments or managing transactive group memory (by creating and managing shared knowledge across group members).

The **Awareness** category relates to knowledge about the environment, more specifically about cognitive awareness (what do I and other people know), behavioral awareness (what do other people do) and social awareness (emotional state of other group members (Ma *et al.* 2020)). As such, Hesse’s social skill of perspective taking corresponds to a type of social awareness. It also englobes Meier *et al.* (2007)’s interpersonal relationship category since it involves processes such as sensibility for hierarchical orders and potential conflicts that are a type of awareness essential to maintain collaboration. Examples of awareness

processes include self-evaluation (gaining awareness of personal strengths and weaknesses), pooling from transactive memory (gaining awareness of knowledge, strengths and weaknesses of others) or assuming responsibility for aspects of the activity itself. While those processes are not directly visible to an observer, they feed participative processes that reflect their presence within a group (such as taking part in an activity and informing others about its progress).

The **Coordination** category relates to collaboration processes that coordinate how the task is addressed by the group. This category exists in all three frameworks (called “task regulation” in Hesse *et al.* (2015)’s framework). This category encompasses processes for resource management, planning (goal negotiation and expectations) and the organization of contributions from group members. Group processing is another important coordinative process describing the ability of a group to assess and evaluate their strategies for task completion and adapt them accordingly through negotiation (D. W. Johnson and R. T. Johnson 1989).

These three categories are at the center of our collaborative process vision (figure 2.2 ②). However, there are also elements from these three frameworks that do not fit these categories. Notably, Hesse *et al.* (2015) present the transactive memory system (TMS) as a process, when in fact it is a cognitive artefact. Indeed, Wegner (1987) (also cited by Hesse *et al.*) defined it as “a set of individual memory systems in combination with the communication that takes place between individuals (Wegner, Giuliano, & Hertel, 1985)”. This is an artefact that only has its *raison d’être* within the group context. Similar concepts of this nature are the consensus reached through Meier *et al.* (2007) concept of “Joint Information Processing” (otherwise known in literature as Grounding or Joint Problem Space - JPS), the developed hypothesis in groups and developed plans and strategies by the group. Roschelle and S. D. Teasley (1995b) introduced the term **Cognitive Space** that regroups these artefacts during collaboration. We thus extend our collaborative process space by this notion (figure 2.2 ③). Similarly, while building interpersonal relationships (part of Meier *et al.*’s framework), is a process, the relationships themselves are not. Collaborative processes have been approached differently by P. Kirschner *et al.* (2015), arguing that there are social processes, nourishing a **Social Space** (e.g. through encouraging peers) and task-related processes to establish common conceptual ground among group members. Their framework distinguishes cognitive from social performance. We thus extend the process space of our PAC framework by the notion of a social space (figure 2.2 ④).

Input

Collaborative processes and skills are but one aspect of how and why collaboration comes to be. As Pierre Dillenbourg (1999) points out, there is no guarantee that collaboration will occur, but the likelihood can be increased by establishing favorable **conditions**. The selection and design of activities, for instance, play a pivotal role in fostering collaboration. Conditions, as mentioned previously, are part of the input of a process. The **Input** of the collaborative process designates the conditions under which the process takes place: the problem, task or activity, the environment (tools, resources, constraints) and the individuals with their individual knowledge, cognitive (task-related) and collaborative skills. The latter provide the interface to Hesse *et al.* (2015) framework of collaborative skills (figure 2.2 (5)). Collaboration isn't the preferred working style for groups since it is often less efficient than other forms of collective work. Cooperation offers advantages like task parallelization and reduced cognitive load per individual. Hierarchical structures further diminish cognitive load by narrowing the information spaces required for specialized subtasks. However, this mode of operation impedes learning since learning thrives on exchanges. To foster collaboration within a team, D. W. Johnson and R. T. Johnson (2009) outlined conditions for successful collaboration through social skills, promotive interaction, positive interdependence, group processing, and individual and group accountability. Social skills and promotive Interaction involve individuals encouraging and facilitating each other's efforts to achieve the group's objectives. Group processing encompasses various levels of self-reflection and regulation concerning the needs and goals of others in the group, as well as shared reflection and regulation. These metacognitive skills necessitate metacognitive assessments, where members provide feedback to one another and reflect on it to determine the effectiveness and efficiency of individual or group actions. Positive interdependence binds team members together, ensuring that no individual can succeed unless all group members do ("sink and swim" principle). This can be achieved, for instance, by strategically distributing necessary knowledge for task completion among team members, thereby compelling information exchange and collaboration. Finally, group and individual accountability ensure that individuals are held responsible for both their own and the group's performance. When a person's performance impacts their collaborators' outcomes, group members feel accountable for their peer's welfare as well as their own. "Failing oneself is bad, but failing others as well as oneself is worse" (*ibid.*). This element can be integrated in our current structure: Social skills are part of the skillset a participant has and are thus input conditions, their realization through promotive interactions

in turn a participative process. Positive interdependence is either existent beforehand through distributed knowledge among participants or can be enforced through activity design, but is, in either case, an input element. Group processing can be considered the monitoring of a plan, Hesse et al. mention among task regulation skills and the coordination Meier *et al.* (2007) features in their framework. As such, it is a coordinative process in our PAC framework.

Output

The **Output** of a collaborative process can be classified into task-related outcomes, such as products and artifacts, and learning outcomes. During collaboration, members are exposed to their peers' task-related perspectives, solution strategies, and values, which challenge their own. This aspect of collaboration underscores its significance for both learning and work: collaboration stimulates learning processes while also facilitating the achievement of outcomes related to complex tasks. Consequently, Computer-Supported Collaborative Learning (CSCL) adjusts conditions to optimize learning outcomes, whereas Computer-Supported Cooperative Work (CSCW) operates within more fixed circumstances and a focus on the (task related) product of the collaborative process. In the previous chapter, we distinguished learning of collaboration from cooperative learning. We noted that cooperative learning is destined to convey educational content by providing collaborative scaffolding, while learning of collaboration focuses on the application and improvement of collaborative skills. These two concepts appear in our process model through different foci on outcomes: cooperative learning results and aims at learning outcomes whereas learning of collaboration focuses on collaborative skills. Both are not mutually exclusive and exist in a continuum of collaborative learning. Learning setups can target both, but targeting both increases complexity of configuration, monitoring and evaluation. Moreover, participants engaged in collaboration have the opportunity to practice and enhance their collaborative skills independently of focus. Finally, the development of relationships and the modification of individuals' values beyond the collaboration itself represent a social outcome (Griffiths *et al.* 2021) oftentimes desirable in the context of teambuilding activities.

2.1.3 Conclusion on the Core PAC Framework

In this section, we presented the result of our attempt to negotiate a joint framework from key contributions in CSCL literature.

We established a process based structure and regrouped five frameworks in **Input**, **Process** and **Output**, the result of which is illustrated in figure 2.1. We have identified three categories of collaborative processes: **Participation**, **Awareness** and **Coordination**. Processes of all three categories and input conditions act on a **Cognitive Space** and a **Social Space**. The output of the collaborative process can either be one or multiple elements of the following: a product, a learning outcome, collaborative skills or social relations. The input of the collaborative process is composed of the environment in which it takes place, including the activity and the participants with their different skills, knowledge and values.

The success and smoothness of the operation confirm the idea that the different frameworks are partial perspectives on the same phenomenon. Interestingly, the proposed PAC framework is based on including all frameworks with only minor adjustments or clarification (e.g. the notion of the TMS). Through the four outcomes we can distinguish collaborative learning, both learning of collaboration and cooperative learning from other collaborative activities in the domain of CSCW such as teambuilding (social outcome) or collaborative work itself (focus on a task outcome). The framework also illustrates how learning outcomes can occur through the design of the activity: In the context of collaborative learning, conflicts in the social or cognitive space can be a design feature to motivate group members to invest the mental effort required for learning to occur (Grund *et al.* 2024). The established PAC process categories can now be extended through indicators to evaluate the effect that tools or functionalities have on the different aspects of collaboration. It hereby provides a step to bridge “clicks and concepts” (Martinez-Maldonado *et al.* 2021). Finally, the framework is coherent with the definition for collaboration established previously (“ a set of collective processes in which two or more entities engage in a joint effort towards a common goal by establishing common ground”): The entities are part of the collaborative process input, the joint effort is reflected in the output and common ground is established in the cognitive space.

2.2 Extended PAC Framework

The previously presented Core PAC framework was built on eight major frameworks in the field. The following **extended version of the PAC framework** is based on a keyword literature review on collaborative frameworks and enhanced by major, albeit more narrowly targeted, contributions on specific concepts and conditions of collaboration. Hence, our first motivation is to thoroughly confront our previous work with other contributions and consequently, obtain **a more detailed version** of the nature of collaboration and collaborative learning.

The application context is also widened: Whereas the previous simplified core version was initially designed to map existing tool functionalities on collaborative process dimensions, the following work is an attempt to **bridge theory with collaborative analytics**. The question how to link “click and concept” (Martinez-Maldonado *et al.* 2021) has been studied extensively in recent years with the emergence of the field of collaborative analytics. Analytic frameworks attempt to provide indicators to detect and detail collaboration in activities (Cukurova *et al.* 2018). During the construction of the following framework, we discuss the impact of such frameworks on collaborative processes.

A third motivation is to **identify the more complex interconnections** between collaborative concepts. The concept of motivation, for instance, can be impacted and mutually impacts (is thus linked to) collaborative processes of promotive interactions, a type of nonverbal or verbal participation. Knowledge about such links among collaborative processes can, in turn, change how participants interact, making promotive interactions a part of their individual collaborative skillset. Relationships like these illustrate the intricate nature of mechanisms within collaboration that CSCL attempts to reveal, explain, quantify and support, all while dealing with a large number of parameters and processes. Until now, our core PAC framework does not describe these links.

Finally, having realized the complexity of the phenomenon, a closer collaboration among CSCL researchers to reveal interconnections and further concepts is our forth motivation. The urgency of conceptual consolidation has been recognized by leading researchers (A. F. Wise and Schwarz 2017) questioning if “one framework to rule them all” is an adequate response to the problem. Rummel (2018)’s take on the “provocations” by Wise *et al.* is that it is very difficult, as a community, to reach common conceptual ground. There is also doubt on the extent to which common ground is required. Rummel for instance proposes a taxonomy to design collaborative activities and analyze collabo-

ration along this taxonomy. Objectively, the most urgent need in terms of consolidation is indeed an **analytics and design framework** due to the fast pace with which technology steadily increases possibilities of collaboration support and automated analysis. Meanwhile, it is clear that there is no single way of analyzing collaboration in the field, which makes comparison of studies and reproducibility difficult (Martinez-Maldonado *et al.* 2021). The same is true for design frameworks. The reason, in both cases, seems to be, that in order to analyze or design environments for collaboration or CL, the research community needs to agree on what those concepts mean in greater detail.

Accordingly, the extended version of the PAC framework in this section was presented at ISLS/CSCL 2024 as a potential collaborative tool for the community. Tools to obtain common ground on topics and problems among communities exist and there is reason to believe that the required tools to create and maintain common ground can be built from research work done by members of the CSCL community (such as Scardamalia (2002)).

2.2.1 Method

Extension of the Core Framework

The extension of the core PAC framework has been conducted through a systematic literature review (figure 2.3) to initially detail collaborative **processes** ①, then detail **input** and output ②, ③ through both the results of the literature review and learning theories. We further extend the framework with analytics ④ and design frameworks ⑤ from our literature review and contributions that we are currently aware of, reflecting the double role of CSCL to both analyze and improve collaboration through tool design.

Finally, we discuss **links** between the PAC framework elements ⑥ from dedicated contributions and results of the literature review. Figure 2.3 shows the elements that have contributed to this extension and the order of subsections in which they are discussed:

1. Process Details: Section 2.2.2
2. Input Details: Section 2.2.3
3. Output Details: Section 2.2.4
4. Adding Analytics Frameworks: Section 2.2.5
5. Adding Design Frameworks: Section 2.2.6
6. Linking Concepts: Section 2.2.7

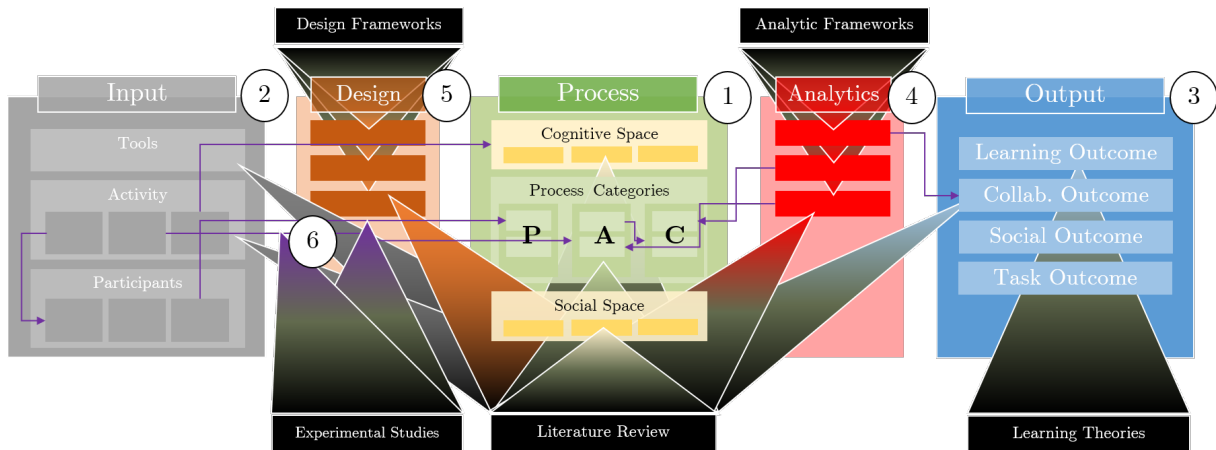


Figure 2.3: The process of extending the PAC Framework by subsection

Framework Literature Review Method

The literature review on frameworks, based on keyword queries, enabled us to detail all three dimensions of the Core PAC framework. The process is outlined in figure 2.4. We included contributions from CSCL, CSCW and research from other domains. For each of the keyword queries “Conceptual collaborative learning framework”, “Conceptual collaboration framework”, “Conceptual framework for collaborative Problem solving”, “CSCL framework” and “CSCL ontology” in google scholar, ERIC and the International Journal of CSCL database, we examined the first 50 results (title and abstract) for the period between 2010 and 2024.

Additionally, we searched the conceptual parts of both editions of the international handbook of CSCL (2013 and 2021), amounting to a total of 10 contributions. After identification of 3 duplicates (papers identified through the keyword research and in the international handbook of CSCL), we screened the 607 records by reading title and abstract. Contributions were included in the eligibility stage based on the framework definition of Jabareen (2009): “a network of linked concepts that together provide a comprehensive understanding of the phenomenon”.

Out of 607 records, 50 matched this definition in their abstract. We then proceeded to study the entire contribution and excluded contributions if the framework did not concern collaborative learning or collaboration (as defined in the previous part). 42 Frameworks were consequently categorized according to their perspective: skills, processes, general aspects, conditions, pedagogical approaches, analytics and design frameworks. The following subsections detail how the retained frameworks inform the different dimensions of

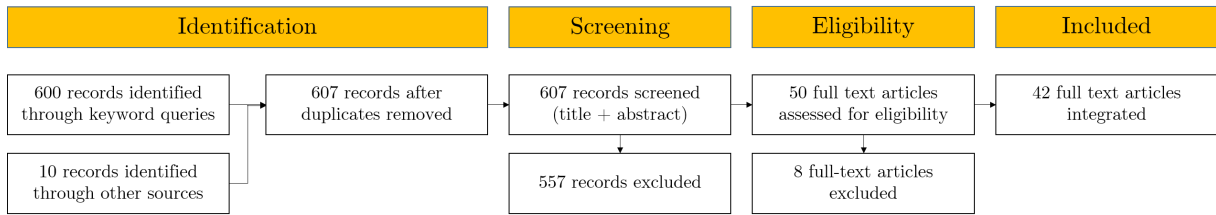


Figure 2.4: PRISMA schema for the selection process of the literature review

the PAC framework, alongside learning theories for the output dimension.

2.2.2 Detailing Collaborative Processes

In the following paragraphs, we detail the three elements of the collaborative process (green rectangle in the PAC framework, figure 2.3): the collaborative process categories PAC, the cognitive and the social space.

Collaborative Processes

Through the comparison of the literature review’s results, we could identify fifteen elements for the three PAC categories (figure 2.5) and two properties that seem applicable to all collaborative processes (all processes have a collaborative cognitive load and can occur in collaborative coupling). These are all detailed bellow.

Coupling Collaborative learning or collaborative work, over extended periods of time, may not require continuous collaboration. It has been observed that group members in physical collaboration may split into subgroups (couple) or temporarily shift to individual work or pause. When rejoining the group after such interludes, a resynchronization with the rest of the group is required. Tang *et al.* (2006) have identified six different configurations in face to face collaborative settings:

1. Both are actively engaged in working on the same problem
2. One person is working and the other “watching closely enough to suggest corrections”
3. Both are working individually on the same problem
4. One person is working, the other is viewing without the ability to provide suggestions
5. One is working, the other person is disengaged

6. Both are working on unrelated problems

Over time, those configurations might change during group work. While (5) might seem like a configuration to avoid during collaborative group works, it has been acknowledged, that reflective pauses are an important part of collaboration to allow group members sort their thoughts before re-engaging in collaborative processes (A. Wise *et al.* 2021). Collaborative coupling is an important aspect for all processes, since processes such as awareness can be maintained even during collaborative coupling phases, whereas active processes such as task division ideally are bound to the entire group to maintain a sound social space. Such relationships will be discussed later in subsection “Linking the Concepts”.

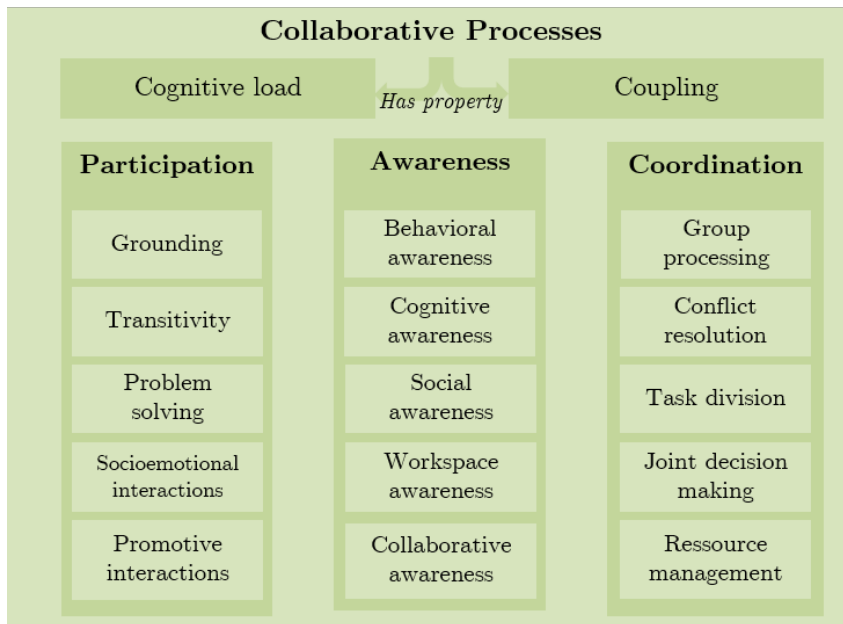


Figure 2.5: Elements of the extended PAC framework’s collaborative process

Cognitive Load Collaborative cognitive load is a property of collaboration that is based on the observation of limited human cognitive resources (J. Sweller 1988). It is a theory to explain why and how learning fails or succeeds. P. A. Kirschner *et al.* (2018) transferred this notion to collaboration, establishing the collaborative cognitive load theory. Building on the concept of the cognitive architecture presented by J. Sweller and S. Sweller (2006) and the distinction between primary and secondary knowledge by Geary (2004), P. A. Kirschner *et al.* (2018) argue that the process of collaboration induces cognitive load. Combined with the cognitive load for the learning of secondary knowledge (all skills and knowledge requiring schooling), the theory provides explanations for the failure

or success of collaboration. For instance, Kirschner et al. argue that group members with low collaborative skills experience high cognitive load during collaboration. If the activity also induces high cognitive load (for example if the activity context is new) it is likely that collaboration and/or activity success is impeded. In the context of the PAC framework, we can attribute a cognitive load to any component of the collaborative processes. Furthermore, we can qualify this load in approximate terms. For instance, behavioral awareness in physical collaboration has low cognitive load. This changes in collaborative settings such as virtual reality or video conferencing, where less of the normal stimuli are available and members have to build behavioral awareness through explicit focus on the information from the communication tool (Riedl 2022). This also applies to social awareness, since the correct interpretation of a social state of other group members necessitates more attention when mediated through computer support (e.g. due to the video stream quality). Workspace awareness seems to have a variable cognitive load associated to the relative complexity of the workspace itself. In specific contexts such as brainstorming, functionality to sort and group virtual items might contribute to better collaboration where the hypothesized link would be a reduced cognitive load for workspace awareness. In turn, we can infer that processes like verbal and nonverbal communication draw low cognitive load, since they are part of the primary knowledge/skills (J. Sweller 1988). It remains to be seen how different forms of communication (e.g. promotive interactions or transactive discourse) differ in their cognitive load.

Participative processes S. D. Teasley (1997), Weinberger and F. Fischer (2006) and Vogel *et al.* (2023) have contributed to the effort to elucidate **transactive interactions**. While there appears to be general consensus on a definition that transactive discourse elements are elements which build on other's contributions, conceptual categorizations vary. Weinberger and Fischer provide a five step scale of externalization, elicitation, quick consensus building, interaction-oriented-consensus building and conflict-oriented consensus building, while Vogel distinguishes between novelty and reference discourse. Novelty transactive actions map to the externalization category in Weinberger and Fischer's scale, and reference transactivity to the remaining four categories. Further research to combine a larger corpus on specialized work is required to further detail this particular process.

Relatedly, participation in **problem solving** may involve participation at different levels, depending on the models that have been developed for different contexts: IDEAL, PDCA, 8D, Simplex, TRIZ form but an example of a subset of the different problem solving models developed with common but also differing elements. Depending on collab-

orative input context, one model is more suitable than another, which holds true for the majority of elements of our framework which might be present to a different degree in one context or another. For any collaborative problem solving to take place however, the process of **grounding** is fundamental. Grounding describes how two or more entities come to a shared understanding of a topic (Clark 1996). Speakers actively seek understanding through questions, describing the statements of others in their own words or try to repair dissonances.

The concept of **promotive interactions** has been extensively studied by researchers such as D. W. Johnson and R. T. Johnson (2009). The authors view those interactions as a consequence of positive interdependence and define it as “individuals encourage[ing] and facilitat[ing] each other’s efforts to accomplish the group’s goals”. The authors have compiled a list of these interactions in *An educational psychology success story: Social interdependence theory and cooperative learning*:

1. “Acting in trustworthy ways”
2. “Exchanging needed resources”
3. “Providing efficient and effective help”
4. “Being motivated to strive for mutual benefit”
5. “Advocating exerting effort to achieve mutual goals”
6. “Having a moderate level of arousal, characterized by low anxiety and stress”
7. “Influencing each other’s efforts to achieve the group’s goals”
8. “Providing group mates with feedback in order to improve their subsequent performance of assigned tasks”
9. “Challenging each other’s reasoning and conclusions in order to promote higher quality decision making and greater creativity”
10. “Taking the perspectives of others more accurately and thus being better able to explore different points of view”

Element (9) closely resembles the transactive interactions defined by Weinberger and F. Fischer (2006). Conceptual conflicts or potential overlaps between elements of different

concepts are unavoidable and show the interest of a common framework as collaborative artefact for the CSCL community. In this particular case, it seems that the interaction has both positive impact on the performance and group morale.

Socioemotional Interaction comprises actions to build and maintain the social space in addition to promotive interactions. Unresolved socio-emotional conflicts may divert cognitive attention away from task related challenges (Näykki *et al.* 2014). Isohätälä *et al.* (2020) distinguishes two categories: socioemotional support and humor. Actions that fall in the first category involve “encouraging, praising, complimenting, apologizing, explicating group cohesion, and expressing sympathy”. Other forms of socioemotional interactions include socio-emotional conflict resolution, complimenting, the attribution of roles, humor or help seeking. Again, we notice overlapping with the concept of promotive interactions. Depending on a possible refinement of both definitions, Socioemotional interaction might be considered an umbrella term under which promotive interactions can be regrouped. Humor has been identified by Kurtzberg *et al.* (2009) as a trust-building mechanism in asynchronous email exchanges and Volet *et al.* (2009)’s research suggest it might facilitate co-regulated knowledge building. Help seeking has been linked to “socioemotional interactions, namely respect and encouragement of participation” (Isohätälä *et al.* 2020). As such it qualifies as one of the “trustworthy actions” outlined by D. W. Johnson and R. T. Johnson (2009). Näykki *et al.* (2014) highlight the importance of socioemotional conflict management as part of group work. The advantage of diversity and cognitive conflicts that collaboration and collaborative learning are designed to provoke, oftentimes spark also socioemotional conflict situations that the group has to deal with (Garcia-Sanjuan *et al.* 2018).

Coordinative processes In our framework, this last socioemotional interaction is part of the coordinative collaborative process group, among the processes of conflict resolution. Conflict resolution both include the management of cognitive and social conflicts during group work. Distinguishing and appropriately addressing either type of conflict is a central collaborative skill.

Group processing is a concept with two major models. D. W. Johnson *et al.* (1990) distinguish the counseling model that posits a positive feedback chain of self-examination leading to insights which in turn results in increased effectiveness. The second model, introduced by D. W. Johnson (1979)) features external feedback on the group procedures and strategies deployed to attain a goal. Bertucci *et al.* (2012) for instance have reported an increase of collaborative performance in subsequent tasks. Group processing also appears

to have benefits during a task itself as a study by Rasker *et al.* (2000) demonstrates.

Task division refers to the distribution of tasks to members when possible. It introduces individual accountability and consequently presents the potential to reduce social loafing, which can lead to socio-emotional conflicts. **Joint decision making** in turn fosters shared responsibility, when the group has to take decisions on, for example, problem solving strategies to implement. Its presence introduces shared accountability, since the decision is collectively agreed on.

Resource management is an essential aspect of collaboration. In the context of collaborative discourse, time is a limited resource that has to be shared among members (Bachour *et al.* 2010). Territoriality is an aspect within the working space which has emerged as the group manages individual and group spaces (S. D. Scott *et al.* 2004). Tools also constitute a resource that has to be shared, varying, depending on the number of entry points and affordances. Finally, participants also have to manage differences in skills and knowledge within the group. Knowledge gaps have to be identified in order to succeed in the group activity (P. A. Kirschner *et al.* 2018).

Awareness processes Mateescu *et al.* (2019) identified among their literature review a category of Workspace awareness, defined as “understanding another person’s interactions with the shared workspace. Ma *et al.* (2020) provide a complementary framework on awareness, identifying three other types:

1. **Cognitive awareness** is knowledge about who knows what in a group
2. **Social awareness** relates to the emotional state of peers
3. **Behavioral awareness** refers to information what other group members are doing

Behavioral awareness seems to overlap with workspace awareness. But while behavioral awareness in Ma *et al.* (*ibid.*)’s (2020) framework refers to awareness of actions, Mateescu *et al.* (2019)’s category refers to the awareness of intentions. While the social awareness of Ma *et al.* fits the social space, cognitive awareness is restrained but to a part of the cognitive space (as will demonstrate the next section). We therefore propose an extended definition to cognitive awareness as critical awareness to the cognitive space (awareness to who knows what, but also awareness about past group decisions, common concepts and solution approaches). Finally, the process of **Collaborative awareness** seems important to us as a novel type of awareness: Awareness on the presence and quality of collaborative processes themselves. It is a notion inspired by metacognition on the individual

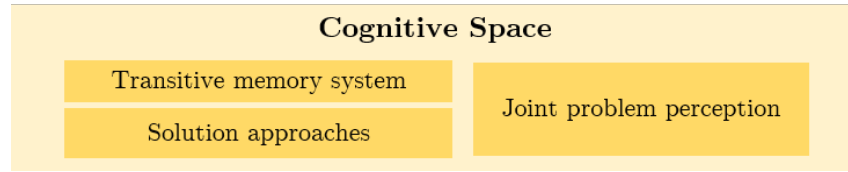


Figure 2.6: Elements of the cognitive space

level. Stahl *et al.* (2006) theorized that the collaboration taking place in a group could be equated to the internal thinking of an individual. Metacognition is considered an important part in student’s learning, and likewise we hypothesize that beyond the importance of self-organization in groups, collaborative awareness as basis for meta-self-organization (managing and actively supporting collaborative processes) may be a crucial process and skill to acquire to support collaboration.

Cognitive Space

In the previous section we highlighted the limits of Ma *et al.* (2020)’s definition of cognitive awareness. Awareness of who knows what within the group is indeed an essential skill and process to make use of the combined cognitive potential of a group, but knowledge about what the group knows is just as crucial. **Cognitive space** (also called collective working space by P. Kirschner *et al.* (2015)) refers to a common understanding of problems and solutions (Borge and Mercier 2019). The group actively engages in its construction (requiring active participation), management (upon arrival of new information) and repair (negotiate diverging visions). Once a **joint problem perception** (also called "Joint problem space" in literature) is established, groups can discuss hypothesis about how to solve the problem at hand – collect ideas on the origin and the mechanisms, establish theories and **solution approaches**. While activities like brainstorming are targeting a specific aspect of the establishment of the cognitive space, problem based learning, for instance, is well suited to stimulate each aspect of a cognitive group space (illustrated in figure 2.6). The cognitive space requires a substantial cognitive capacity to be established and maintained. Groups consequently establish what is known as Transitive Memory System (TMS) to elevate the cognitive load required (which in turn helps improve cognitive awareness).

The concept of a **Transitive Memory System** has been developed by Wegner (1987) in *Transactive Memory: A contemporary Analysis of the Group Mind*. The authors postulate that the concept of external memory can be applied not only to external objects

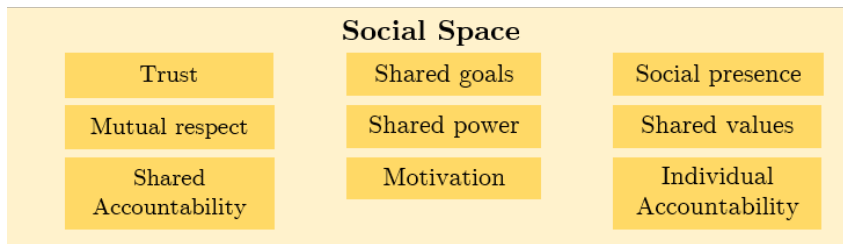


Figure 2.7: The elements of the collaborative social space

holding information, such as agendas, books or hard drives, but to other people as well. Through processes of communication, a group manages information kept in individual’s minds through the maintaining of pointers to the information itself (information on who knows what) on the group level. Through this construct, information is accessed during the retrieval stage through the use of these pointers – when one group member makes a request for the information by asking another member about it. The conversation partner may be either at the origin of the information or has the pointer to/knows the person who knows it. The knowledge about who knows what, constitutes a type of awareness, and consequently, transactive retrieval and storage can be mapped on the process categories of participation and awareness, since the storage requires participation through communication which in turn builds cognitive awareness, involved in the retrieval process. The information pointers themselves are located in the cognitive space of the group, since they only exist in the context of the group.

Social Space

A sound **social space** is regarded by Kreijns *et al.* (2013) as an essential element for “CSCL pedagogy [to] be successfully applied”. Kreijns et al. define a social space as “the network of interpersonal/social relationships among group members embedded in the group’s norms and values, rules and roles, beliefs and ideas”.

The authors further state, that **Social Presence** is a necessary condition for the development of a sound social space, stating that a sound social space is reached “when these group structures manifest themselves by strong relationships, group cohesiveness, trust and respect, feelings of belonging, satisfaction, and a sense of community”. Social presence has been defined by Weidlich *et al.* (2018) as “the psychological phenomenon that the other is perceived as “real” in the communication, the subjective feeling of being with other salient social actors in a technologically mediated space”. Thus, the issue of social

presence is especially central to virtual reality or online setups, but gains importance for physical settings with non-human agents, such as social robots (N. Chen *et al.* 2023).

Alozie *et al.* (2023) also identify **Shared values, motivation** and **shared power** as important attributes of collaboration (figure 2.7). Shared power under the concept of horizontal hierarchies has been previously identified as a property of successful collaboration by Pierre Dillenbourg (1999). From the previous section, we infer that **mutual respect** and consensus of **shared goals** also reside in the social space. D. W. Johnson and R. T. Johnson (2009) highlight the importance of shared and **individual accountability** within a group to avoid detrimental phenomena like social loafing or free riding. Figure 2.8 summarizes the collaborative elements identified as collaborative processes and elements of the cognitive and social space in this section in one schema.

2.2.3 Detailing Input

In this section, we detail the collaborative input of the Core PAC framework. We first propose a detailed version of the environment, most notably the collaborative workspace, tools and the activity, before detailing participants. We use the cardinality notation used in the Unified Modeling Language (UML) to frame the scope of each input variable where possible.

Environment

Many frameworks (Hesse *et al.* (2015), D. W. Johnson and R. T. Johnson (2004), Marjan Laal (2013), Meier *et al.* (2007)) include conditions for successful collaboration. Without favorable conditions, collaboration or collaborative learning is unlikely to occur. This aspect is based on the works of D. W. Johnson and R. T. Johnson (2004) and Pierre Dillenbourg (1999) who observed that for successful collaboration, social skills, promotive interaction and group processing abilities as well as positive interdependence and individual/group accountability have to be present among group members. These conditions are related to one or multiple **environments** in which collaboration occurs (multiple environments occur for example in distributed collaboration) and its characteristics (figure 2.9).

We identified the **time** and **space(s)** in which the activity takes place, of which the **workspace** (either virtual, physical or a combination of both) is a part of. The available **tools** used in the activity (e.g. computer support) are situated on a gradient between vir-

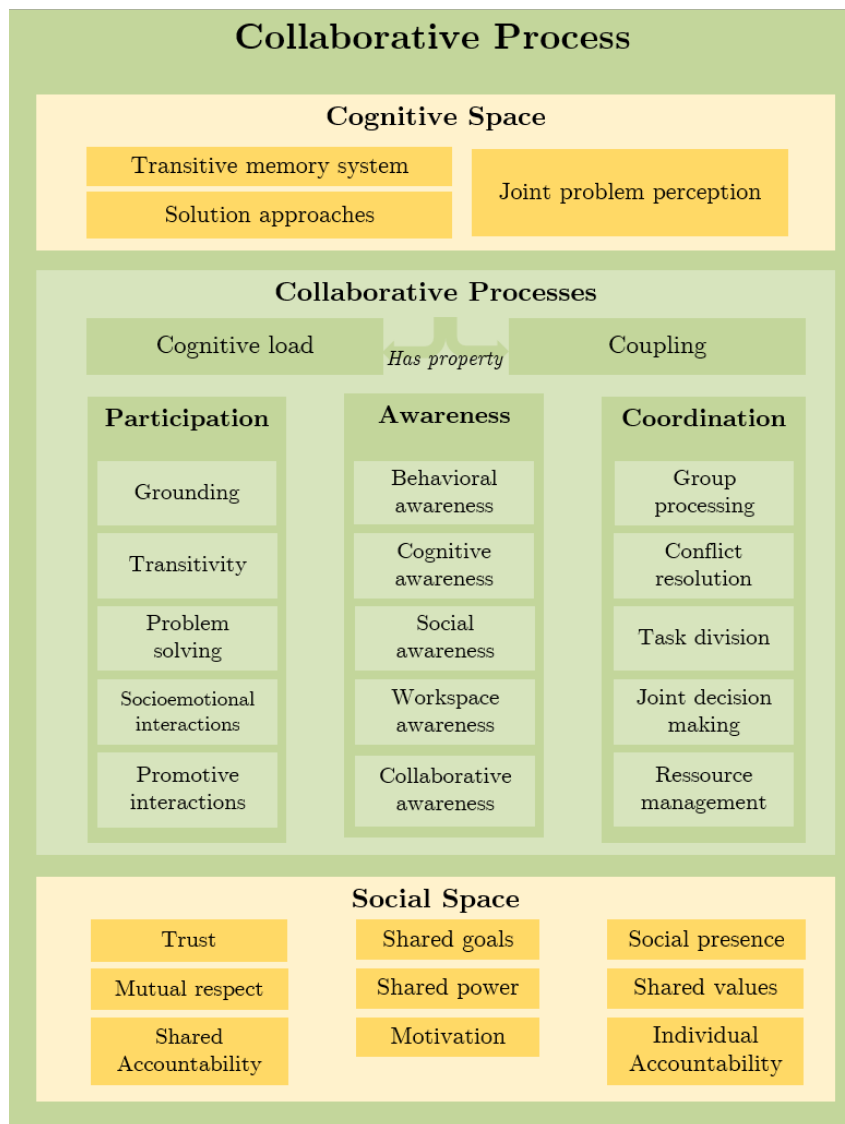


Figure 2.8: The detailed collaborative process part of the extended PAC framework

tual and tangible, may include an adaptive design (for example to participant’s knowledge level) or can adapt themselves during the activity dynamically to the group’s or group member’s behavior. Tools provide one or multiple interaction types and have one or multiple functionalities intended to support collaboration. Collaboration can occur without or multiple tools. Concerning the **type** of the activity, Chi and Wylie (2014) provide a

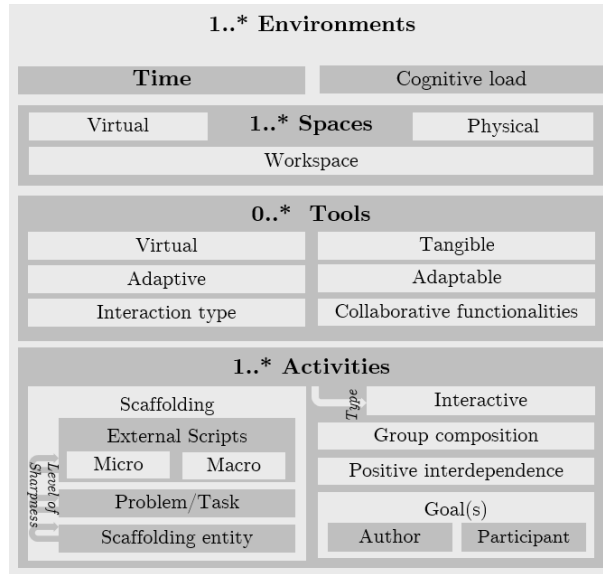


Figure 2.9: Elements of the environment

general classification for learning activities in the ICAP framework, ranging from passive, active, constructive to interactive. Only the interactive type involves interactions with a tutor or peer through transactive discourse. Thus, only interactive activities seem of interest for collaborative learning, an observation met halfway with P. A. Kirschner *et al.* (2018)’s observation that the **problem** or task given has to draw higher than available cognitive load amongst individuals, as to make interactions necessary for success. Problems or tasks of collaborative activities have been categorized as well-defined (task-related goals are clearly defined, strategies outlined etc.), ill-defined (absence of objectives or strategies), or wicked, featuring dynamic requirements or contradictory instructions by Skaburskis (2008). Kirschner et al. argue that ill-defined or wicked problems are particularly well-suited for collaborative settings, giving a reason to group members to engage in collaboration in the light of a complexity beyond individual cognitive abilities. The **goal** type allows for a more appropriate distinction of activities: Given the different outcomes of collaboration (task, learning, collaborative skill or social outcome), the goals can be qualified accordingly. Furthermore, the explicit goal in the activity might differ from the goal

the activity author has set out – for example the pedagogical goal “improve navigational skills” is different from a possible task assignment “draw all landmarks on a map”. Another property of collaborative activities may be **positive interdependence** ingrained in the activity design. An activity can implement for example the jigsaw method, a prominent example of cooperative learning: students do not have to manage resources or emit hypothesis. The design includes cognitive interdependence through **rules** and the **roles** of students, thus reducing the necessity to manage distribution of tasks and structure social interactions. Explicitly attributing roles can be indeed a strategy to reduce cognitive load in activities, if demanding content has to be learnt, since the distribution of roles within a group is a negotiation that takes place during the first stages of team building (Bonebright 2010a) and thus induces cognitive load to the activity if team members are unfamiliar with each other.

Script frameworks provide another perspective as well as elements to and on collaboration and group interactions. Script theory states that for a certain type of situation, humans have procedures and organize their internal knowledge about those situations in “internal scripts” (for example, a script “restaurant visit” may include the process of waiting to be seated, being handed a menu, etc.). External scripts are explicit instructions for procedures to follow in a situation (e.g. flight preparation protocols). Internal collaborative scripts are part of the input that group members bring to a collaborative setting, similar to collaborative skills (Schank and Abelson 2013). Collaborative scripts are knowledge about collaboration (together with knowledge about collaborative processes). External scripting can thus aid groups (and individuals) to engage in successful collaboration.

Pierre Dillenbourg and Jermann (2010) classified scripts into micro and macro scripts. **Micro** scripts directly provide scaffolding for conversations, while **macro** scripts define roles and other parameters in the activity. The use of scripting can lead to three results: under-scripting, over-scripting and optimal scripting. X. Wang and Mu (2017) link optimal scripting to the zone of proximal development between the learner and a more knowledgeable entity. Under-scripting refers to instructions of the script that are beyond the understanding of the learner. On the other hand, over-scripting provides guidance on a process that is already present as internal script among the learner. Over- and under-scripting might occur both in quantity (too much scripting) and quality (if a learner has already a complete internal script, detailing every component induces unnecessary cognitive load, similarly to the expertise reversal effect). Importantly, the differentiation between macro and micro scripts is not the only categorization: F. Fischer *et al.* (2013),

for example, have established a script theory with the first of seven principles stating: “When participating in a CSCL practice, the learner’s understanding of and acting in this situation is guided by dynamically configured and reconfigured internal collaboration scripts consisting of play, scene, scriptlet, and role components”. Literature further distinguishes different kinds of scripts: fading, static, adaptable and adaptive scripts (X. Wang and Mu 2017). In our framework, external scripts are part of the scaffolding aspect within the activity, and internal scripts are part of the participant’s collaborative skillset. Scaffolding may also be used to create socio-cognitive conflicts within a group. Socio-cognitive conflict theory states that learning can occur through opposing points of view between learners and stipulates the benefits of negotiation of those points of view for the learning process (Butera and Darnon 2010). One key skill learners are supposed to acquire is the ability to falsify, which in collaborative learning scenarios can be practiced (Sacco and Bucciarelli 2008). From this point of view, group composition is an interesting variable for educators to take into account when initiating group work (to trigger discussions between students with diverging points of view).

The role of the educator, or any other **Scaffolding Entity** may be defined as well in the activity, since teaching can be defined as the activity of actively steering and optimizing knowledge building (Lave and Wenger 1991). Marjan Laal and Mozghan Laal (2012) points out that the role of the teacher may either be to define and control the roles attributed to students in groups (cooperative learning) or to only intervene on the process level (assist or stimulate conflict resolution etc.).

Participants

The groups or dyads, operating in the aforementioned environment(s), are constituted by two or more participants. The **social background** of participants, and more particularly, diversity among members can influence collaborative processes. Beyond task knowledge diversity (P. A. Kirschner *et al.* 2018), Page (2007) also argues through his “toolbox framework” for positive impact by skill and value diversity. A person’s toolbox’s content is a “product of identity, experience and training”. Page also proposes this vision as an alternative to the unidimensional measurement of intelligence scores. The toolbox framework states that a person has different skills, knowledge and values depending on their previous experiences and demographic contexts. Some of these skills, knowledge and values are of particular interest to collaboration, such as **collaborative Skills** as defined by Hesse *et al.* (2015), susceptible to support collaborative processes acting both on cognitive

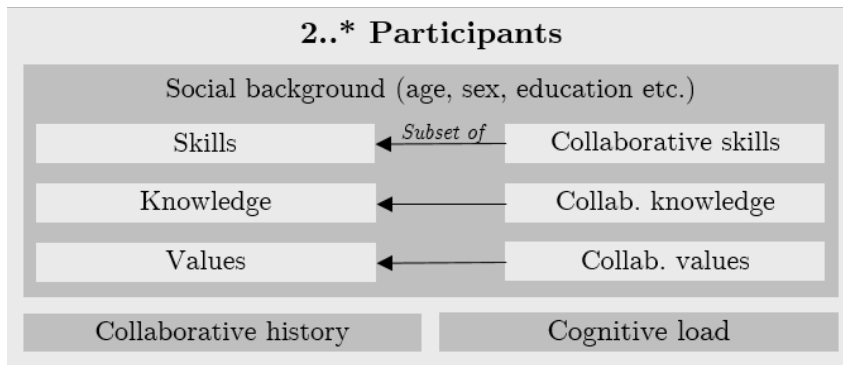


Figure 2.10: Detailing the Input part "Participants"

and social space (figure 2.10). There should be at least one collaboratively skilled person per group so that other group members can engage in collaboration through copying their behavior (P. A. Kirschner *et al.* 2018). As for domain specific knowledge, if domain specific knowledge is available in a group, that is, the group being heterogonous in terms of novices and knowledgeable learners, this “could be favourable for learners with lower levels of prior knowledge” (Kirschner *et al.*). Learning conversations, a concept introduced by R. D. Pea (1992) for instance, implements this observation, underscoring the importance of the conversation between a knowledgeable person and a novice, in turn inspired by Vygotsky (1978)’s zone of proximal development.

Likewise, we define **collaborative knowledge** as knowledge related to the functioning of collaborative processes, knowledge that might be important to establish and repair collaborative processes. Furthermore, the participant’s values, and in particular **collaborative values** (e.g. considering other team members as equals with the same rights to resource access) can facilitate successful collaborative experiences. The importance of a horizontal hierarchy between group members has been pointed out for instance by Edmondson (1999). Consequently, existing hierarchy between group members might lead to hierarchically lower members contributing less and hinder shared responsibility. These three dimensions are negotiated and organized among a group through coordinative processes in the social space. Research on team compositions confirms the presence of those procedures and predispositions (Kreijns *et al.* 2013). P. A. Kirschner *et al.* (2018) include in their framework “prior team experience”, an aspect we have included in our framework as **collaborative history**, designating the experience of group members working together. The combined collaborative input is illustrated in figure 2.11. Interestingly, just as all components of the collaborative process have cognitive load, so have all components

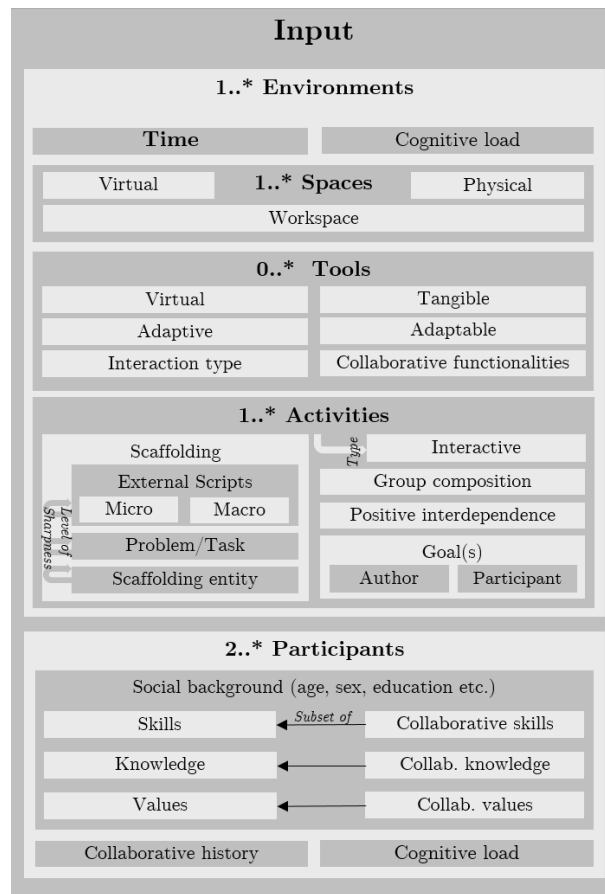


Figure 2.11: Detailed Collaborative Input in the extended PAC framework

of the input. For instance, reducing cognitive load associated to the use of a tool is a central preoccupation in the field of Human-Computer-Interfaces and in the design phase of computer support for collaborative learning, since the learner's main resources should be directed to learning or collaborative processes. Similarly, using an unfamiliar workspace may demand more cognitive resources and working with unfamiliar group members (e.g. in a foreign language) may induce complementary cognitive load.

2.2.4 Detailing Output

In the Core PAC framework, we identified four outcomes of a collaborative activity:

1. Task related outcomes, such as a solution to a problem or a developed product
2. Learning outcomes

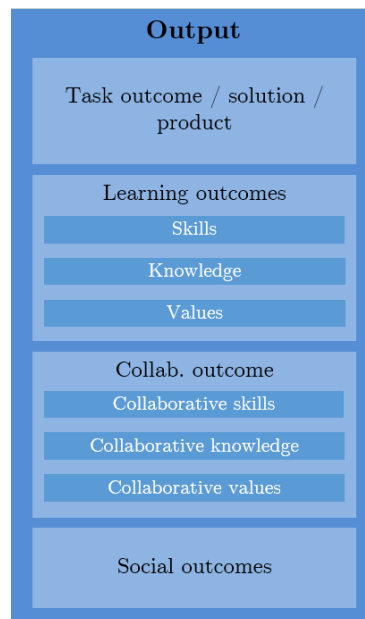


Figure 2.12: The extended PAC framework’s output

3. Collaborative outcomes

4. Social outcomes

Given the context of CSCL in this dissertation, we detail in this section learning outcomes (2) and collaborative outcomes (3). As specified in the previous chapter, cooperative and collaborative learning can be distinguished by their outcome: cooperative learning aims to support collaborative processes for learning, while learning of collaboration, as we termed the historical “collaborative learning” is about learning to collaborate. Learning being involved in either case, we can inform the PAC framework through the bias of learning theories. Lave and Wenger (1991) describe learning as the legitimate peripheral participation in a community through which individuals acquire **Skills**, **Knowledge** and **Values** to become functional parts of society. These three elements therefore detail the learning output type (and interestingly highlights why collaboration seems to be an adequate vehicle for learning, as it emphasizes the learning through participation in group activities). We notice that these three elements are already present on the **Input** side of the collaborative process, among the element of **participants**, underlining the cyclic nature of learning.

On the other hand, while still being actively researched, institutions have identified collaboration itself as the “super skill” of the 21st century and aim to teach students the

necessary skillset (Praharaaj 2022). Coincidentally, engaging in collaboration also allows to improve **Collaborative skills, values and knowledge**, given collaborative skill/-value/knowledge diversity among group members (Cress *et al.* 2021). Collaborative Skills refer to the ability of participants to initiate and maintain collaborative processes. Collaborative values are values inherent to collaboration and necessary for its processes: equity (allowing each participant to participate to the same extent), respect for the contributions of others (refer and build on them, for example in transitive interactions), perseverance (to engage in group processing). Finally, **Collaborative knowledge** refers to knowledge about the collaborative processes, (such as the positive role of promotive interactions). The extended output dimension is illustrated in figure 2.12).

Cooperative learning can thus be contrasted with the learning of collaboration and reveal its similarities: In collaborative learning, collaboration serves as a vehicle to convey skills, knowledge or values. Inversely, teaching/learning collaboration aims at conveying collaborative values, collaborative skills and collaborative knowledge (as defined previously). As we demonstrated in “detailing input”, collaborative skills, values and knowledge can be considered a subset of general skills, values and knowledge. As such, it is debatable whether the two outcomes exist in isolation or, as we argued previously, in a continuum. For either output type, we insist on the potentially latent process of learning (De Houwer *et al.* 2013): The results of the collaborative processes might not be immediate and measurable after a single activity.

2.2.5 Adding Analytic Frameworks

Collaborative analytics is a subfield of CSCL concerned with the analysis of collaboration. The multimodal nature of collaborative datasets and evolving capabilities of analysis through the use of AI and new sensors (Martinez-Maldonado *et al.* 2021) make it another quickly evolving subfield of CSCL. The main source of analysis has long been the collaborative discourse, and consequently, many studies rely on **Conversation Analysis**. More recently, frameworks (e.g. the NISPI framework) that rely on gestures and gaze indicators have been developed (Cukurova *et al.* 2018) with the aim of detecting successful collaboration differently. We distinguish analytic frameworks initially on their target: Do they analyze data on the process level (process-oriented research) or are they interested on the outcomes of collaborative settings (effect-oriented research)? As far as we are aware, there does not exist one universal framework of collaborative indicators. Recent efforts on evaluating the overall quality of collaboration have concentrated on evaluating

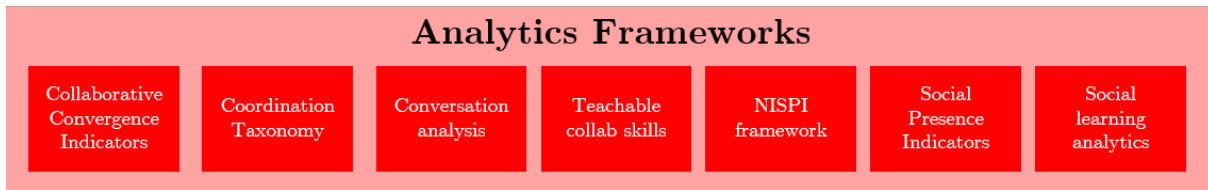


Figure 2.13: Analytics Frameworks in the extended PAC framework

collaborative convergence (Praharaj 2022). Collaborative convergence is an umbrella term based on the symposium paper by S. Teasley *et al.* (2008) entitled *Cognitive Convergence in Collaboration*. The described “cognitive convergence” encompasses works on “inter-subjectivity, co-construction, knowledge convergence, common ground, joint problem space, and transactive reasoning”. Chi (2009) describes knowledge convergence as “the process by which two or more people share mutual understanding through social interactions”. For knowledge convergence to occur, Chi points out that grounding is a necessary process but not sufficient. Furthermore, Chi hypothesizes that convergence occurs through active co-construction of a solution or artefact through transactive interactions. Among the indicators to predict and detect collaborative convergence, Praharaj (2022) provides a list of indicators depicted in table 2.1.

Other prominent indicators of frameworks include joint visual attention (JVA) (“the proportion of times gazes of individuals are aligned by focusing on the same area in the shared object or screen”) introduced by Schneider and R. Pea (2013). Schneider and Blikstein (2018) studied the use of hand movements and posture movements to find a correlation to learning gains. There also have been efforts to measure the presence of components of the social space and their quality such as social presence through a **ten component indicator** based on the Rasch measurement model (Weidlich *et al.* 2018). Recent developments on indicators for coordinative processes have resulted in a **coordination taxonomy**, designed by Maquil *et al.* (2024), detailing the different types of coordination in discourse.

From the point of view of our established collaborative processes, the presented indicators can be combined either with entire process categories (e.g. turn taking frequency for participation) or individual processes, or part of those processes, for example JVA as a nonverbal indicator for behavioral awareness. Not only is there no consensus on the analytical dimension of collaborative indicators, but we argue that further consolidation requires the consequent categorization of the collaborative contexts in which these indicators have been tested and evaluated and how those indicators have been designed (a

Parameters	Indicators	Operationalizing collaboration quality	Space tracked	References
Roles (one leader and other non-leaders)	Topics covered detected from keywords, frequently used keywords and phrases	Topical closeness to meeting agenda, proximity of commonly used words and phrases to the roles	Epistemic	Chandrasegaran et al. (2019), Praharaj et al. (2021b)
Dominance	Total speaking time	Higher equity of total speaking time means less dominance in the group and higher quality of collaboration	Social	Kim et al. (2008), Bachour et al. (2010), Bergstrom and Karahalios (2007), Praharaj et al. (2019)
Active participation	Turn taking frequency	More frequent turn taking changes mean higher active participation and better quality of collaboration	Social	Kim et al. (2015)
Expertise	Overlapped speech	Overlap in speech is an indicator of constructive problem solving, expertise and good CC quality	Social	Zhou et al. (2014), Oviatt et al. (2015)
Rapport	Synchrony in rise and fall of average pitch	Higher synchrony in rise and fall of average pitch indicates higher rapport and better collaboration quality	Social	Lubold and Pon-Barry (2014)
Knowledge construction	co-Knowledge convergence (i.e., the amount of shared knowledge in the group), Cognitive convergence	Increase in convergence (i.e., increase in the shared knowledge) implies increase in collaboration quality	Epistemic	Jeong and Chi (2007), Teasley et al. (2008)

Table 2.1: Indicators for collaborative convergence (Praharaj 2022)

constraint to all eventually established links between collaborative processes, outcomes and conditions for collaboration).

2.2.6 Adding Design Frameworks

In this section, we briefly discuss the compatibility with two design frameworks. Design frameworks establish directives for the design of tools and activities to support collaboration or collaborative learning. Such frameworks are based on “lessons learnt” from designers and experimental results on “what works” for collaborative support and what does not. Design frameworks can be considered an aggregation of the interconnections between Input, Process and Output dimensions (some of which will be presented in the following section). Ideally, the design frameworks’ elements map to the PAC framework since they contain results of experiments – one of the motivations to extend the PAC framework. S. D. Scott *et al.* (2003) have identified seven guidelines for the design of tabletop hardware for collaborative work:

1. Support for simultaneous user actions
2. Consideration for the appropriate arrangements of users – to take into account possible, cultural distance zones for comfortable interaction
3. Shared Access to Physical and Digital Objects
4. Support for the use of physical objects, for example through tangible tokens. Scott *et al.* state that with this affordance, users can draw on known scripts from analog settings
5. Support for transitions between tabletop collaboration and external work: the system should have interfaces through which external, personal contributions can be accessed
6. Support for transitions between individual and group work (e.g. support for collaborative coupling)
7. Support for interactions between users

The first and third design directive relate to users being able to use the system concurrently. This reduces the need for resource management. The fourth and fifth guideline

also aim to reduce cognitive load by allowing users to use known interaction scripts and artefacts. The seventh guideline results from the observation of the value of interactions for collaboration. Regarding our framework, these directives can be represented as link between the tool's functionalities and the collaborative processes they facilitate (see figure 19). It also highlights the possibility to detail further these relationships through the integration of design frameworks. In the next part of this dissertation, we will present a finer grained vision of the tool dimension.

Rummel (2018) propose a taxonomy for the design of CSCL support from a more general point of view. Their taxonomy is a list of the following design features:

1. Goal – interaction/group processes – outcome/result of the collaboration (i.e. an artifact) – individual domain knowledge – social skill (i.e. collaborative competence) – affective outcomes (e.g. satisfaction with the collaboration) – motivational outcomes (e.g. learning motivation, attitude towards future collaboration)
2. Timing – prior to the collaboration (e.g. instruction, training, group formation) – during the collaboration (e.g. prompts, resources): immediate, delayed – after the collaboration (e.g. reflection)
3. Implementation – fixed (one size/time fits all) – adaptive (i.e. automated) – adaptable (i.e. user-based)
4. Delivery agent – human – digital persona (i.e. pedagogical agent) – digital system
5. Target – cognitive (i.e. domain help) – metacognitive (e.g. reflection, employment of learning strategies) – social (e.g. managing the interaction) – affective (e.g. coping with frustration) – motivational (e.g. participation)
6. Granularity – task level – step level – turn level
7. Availability – visible – on demand
8. Directivity – no advice – implicit (i.e. enabling conditions, resources) – explicit: general advice – explicit: specific guidance
9. Foundation – no information on state (i.e. just alert) – show state (i.e. raw data) – show aggregated data (i.e. mean or other indicators) – show interpretation of state (i.e. assessment good vs. bad)

10. Addressee – individual – group
11. Mediation – direct (provided to learner/group in need) – indirect (mediated; e.g. presented to peer, teacher, parent)
12. Coercion – no action required – some/any action is required – specific action is required

The first item, **Goal**, describes the support’s intended impact: Is it intended to support collaborative processes directly, should it help the development of collaborative skills, the learning outcome or the production of the learning artifact? Our framework provides the same activity entity. The proposed categorization however differs from ours in that it proposes “affective and emotional outcomes”, an aspect which we grouped as a social outcome among the output dimension. If collaborative skills are to be learnt, the tool scaffolds the learning of those processes, if it is meant to facilitate those processes through tool mediation, it “supports” those processes which already take place in the collaboration. It further underscores the interconnected nature of activity and tool. The tool serves the goals of the activity. These might relate to the pedagogical goal or directly to the task goal within the activity. The second dimension, **Timing**, addresses when the support intervenes during collaboration. It acknowledges that a collaborative tool may not only operate during the collaboration itself but also before or after the collaborative activity, for reflection or preparatory purposes. This aligns with the definition of computer support in the CSCL context, which encompasses tools that support learners, educators, and researchers in various stages of collaborative learning setups. Hence, we can conclude that tools can intervene at any of the three components of the collaborative processes (input, process and outcome), supporting not only the creativity during the collaborative process but also before and after. Implementation involves how a tool can scaffold the activity or

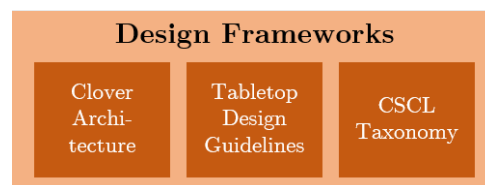


Figure 2.14: Design Frameworks in the extended PAC Framework

cognitive tasks. Tools can be categorized on the criterion whether the functionalities differ from one user to another (adaptability) or if the tool adapts to the user’s interactions

(adaptivity), highlighted in our framework explicitly as a tool attribute. The fifth dimension, Target, is closely related to the Goal dimension. This dimension specifies through which processes the goal will be achieved. For example, from figure 2.20, we can infer that promotive interactions tend to increase motivation. Therefore, the tool may target promotive interactions with the goal of increasing motivation. In our framework, tools target one or multiple collaborative processes, to support the goal(s) of the activity. The targeting aspect is visualized in figure 2.20 as outgoing arrows. While Rummel’s (2018) **taxonomy** constitutes a tool for collaborative activity and support design, other design frameworks directly describe software architectures to show how to implement functionalities.

The **clover architecture**, albeit destined for the CSCW domain, is one example of such a framework for online collaboration, depicting functionalities that are required to establish similar communication affordances to collocated collaborative setups (Laurillau et Nigay, 2002). Identifying and categorizing all groupware design frameworks is beyond the scope of this dissertation, albeit it being an interesting perspective for an extension of the PAC framework. Their specific focus on input parameters and collaborative processes presents a good argument for the position of the Design Frameworks between the Input and Collaborative Process elements in figure 2.15, illustrating all previously discussed elements.

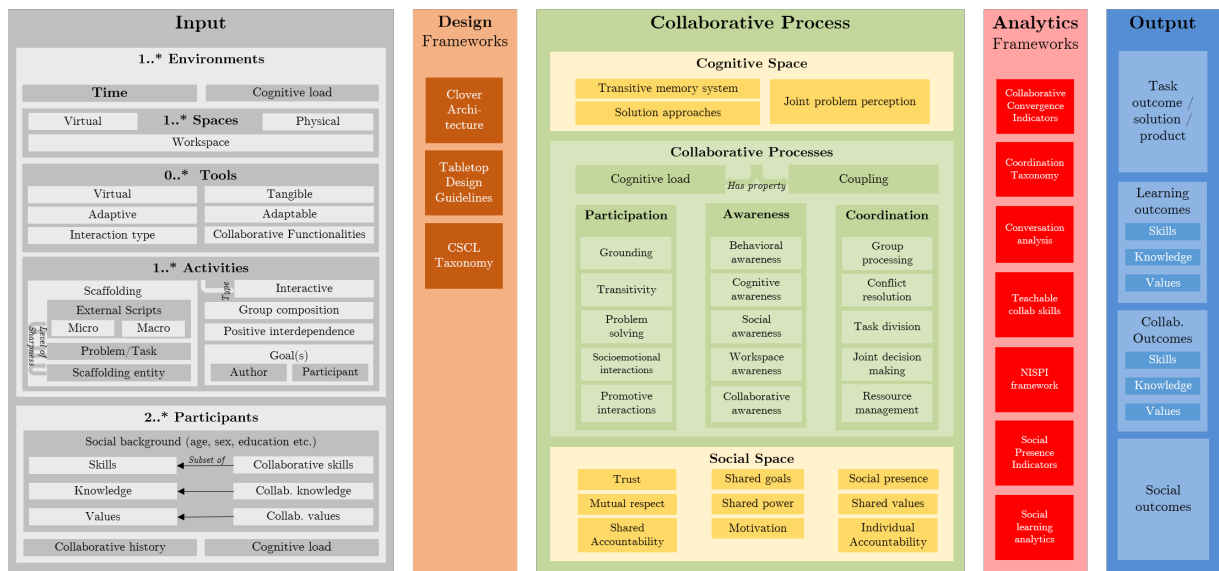


Figure 2.15: Extended PAC Framework

Figure 2.15 is a combination of figure 2.8, 2.11, 2.12, 2.13 and 2.14. The color scheme has been maintained from the Core PAC framework in figure 2.1.

2.2.7 Linking the Concepts

While we have ascended to more detail on the concept level, figure 2.15 holds potential to detail the relationships of those concepts since the previously described collaborative processes and the collaborative input are interdependent. For instance, collaborative awareness can help time group processing procedures or balance participation among members. When the different processes involved lead to successful collaboration, group members might experience what Sawyer (2015) coined collective flow. Collective flow is an extension of flow theory by Csikszentmihalyi (1975) to groups. Hout and O. C. Davis (2019) define team flow as “a shared experience of flow during the execution of interdependent personal tasks in the interest of the team, originating from an optimized team dynamic”. In our framework, collaborative flow can be identified as the synergy of collaborative processes during their successful evocation and participation by all members to the extent required by the activity context. To make evident how the different processes interact, we describe in the following sections firstly broader links between the PAC process categories, before establishing links on the process level, including conditions and analytical frameworks.

Linking PAC Process Categories

The Core Framework’s process categories **Participation, Awareness, and Coordination** can already be put into relation with each other: Illustrated in figure 2.16 is the interconnectedness between the three concepts. Ma *et al.* (2020) theorize the importance of different types of Awareness on meaningful participation. Likewise, participation allows to increase other group member’s awareness on the participating member’s intentions and views. Coordinating the integration of members’ contributions in the activity valorizes contributions and has a positive impact on further participation due to reduced coordination loss (Jhangiani and Tarry 2022). Organizing member contributions also raises workspace awareness and reduces cognitive load by prioritizing and sorting contributions (e.g. during a brainstorm activity). Likewise, participation in coordinative activities has been found to be a cornerstone of successful collaboration itself in order to foster accountability among group members (D. W. Johnson and R. T. Johnson 2009).

Awareness on the elements group members bring to a group work is necessary for purposeful coordinative activities. It is not only important to have awareness on contributed elements, but also awareness on the context in which those contributions are

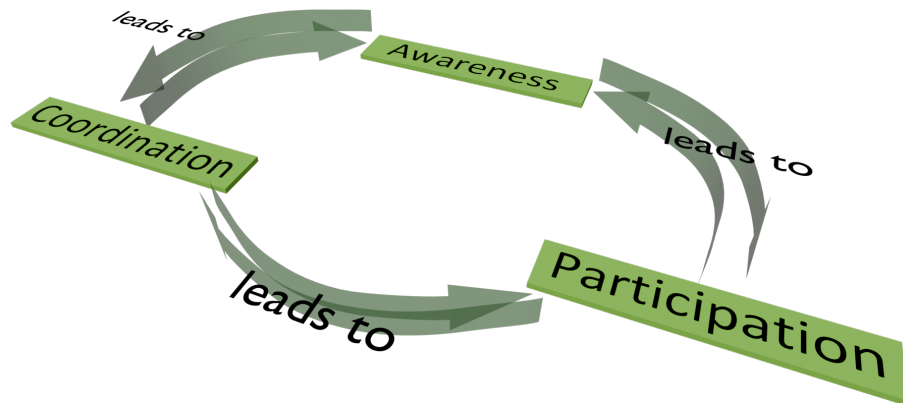


Figure 2.16: Relationships between PAC Process Categories

made. Schegloff (2007) describes in many examples how intentions of conversation elements differ from the actual content of the exchanged messages, requiring group members to eloquently capture the entirety of the contribution of a team member.

We also integrated concepts of cognitive (Roschelle 1992) and social space (Barron 2003) in the previous model, nourished by the different processes. Figure 2.17 illustrates the role of each process category on both the cognitive and social space (central arrows): Group members organize and structure both spaces through the use of coordinative processes. For contributions to be constructive, members have to be aware of the social group dimension (behavioral awareness: “When can I contribute something?”, social awareness: “In which mental state are my peers?”) and the cognitive dimension “Who knows what?” (Ma *et al.* 2020). Processes of all three categories are thus implied in creating and maintaining both cognitive and social space.

Linking Tools to Collaborative Processes

Figure 2.18 depicts the **relationships of tools in the collaborative process**. Participants use tools ①. Tools allow participants to carry out the activity, for instance, exclusively, in distributed online configurations, but might not be the only way to participate in physical settings. Tools might provide functionality for time ② and (work)space management ③. Tools can further provide general affordances or be designed depending on the workspace. In both cases, time and space management tools can elevate collabora-

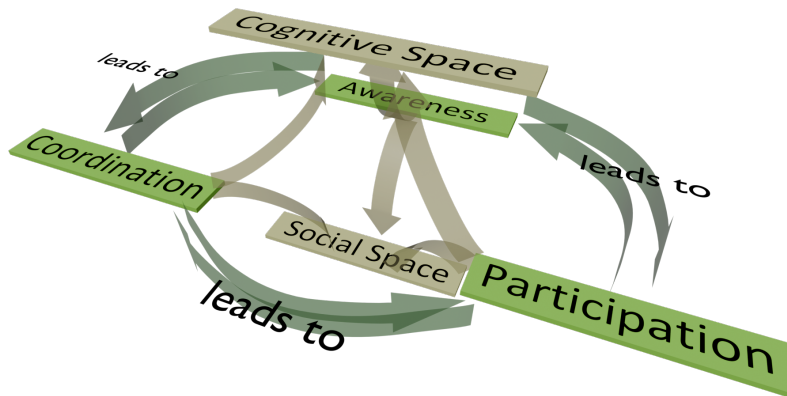


Figure 2.17: Cognitive and Social Space links to Collaborative Processes

tive processes (e.g. resource management) (4). Generally, tools have proven their ability to support collaborative processes of all three categories, as well as the social (4.1) and cognitive (4.2) space. Their design is typically inspired by a design framework.

The relationship between tools and activity is also bidirectional: The activity can be carried out through tools, inversely, the tools can be (an essential) part of the activity (5). The latter function of tools may be further exploited to enforce the rules, roles and interdependence defined by the activity. This facet corresponds to the “structuring” aspect of collaborative tools in Soller *et al.* (2005)’s categorization of CSCL support. Interdependence can, for instance, be achieved by restraining tool functionality to individual participants. If the tool is the primary medium of the activity, rules can be enforced by limiting the user’s permissions accordingly. Moreover, orchestration tools can assist in maintaining the task at a cognitive demanding level, by dynamically removing or adding scaffolding. Tools may also help to produce and evaluate the different outcomes of a collaborative activity, for example through integrated tests, documentation of skills and relationships (6). Additionally, tools can be used by external actors for data collection (7). Advanced systems are able to return the results of a real-time data analysis, for example on collaborative processes, back to the participants.

Linking Activity and Participants to Collaborative Processes

Figure 2.19 shows the role of participants and activities play on collaborative processes. Both have potential to shape all three components of the collaborative process ((1.1))

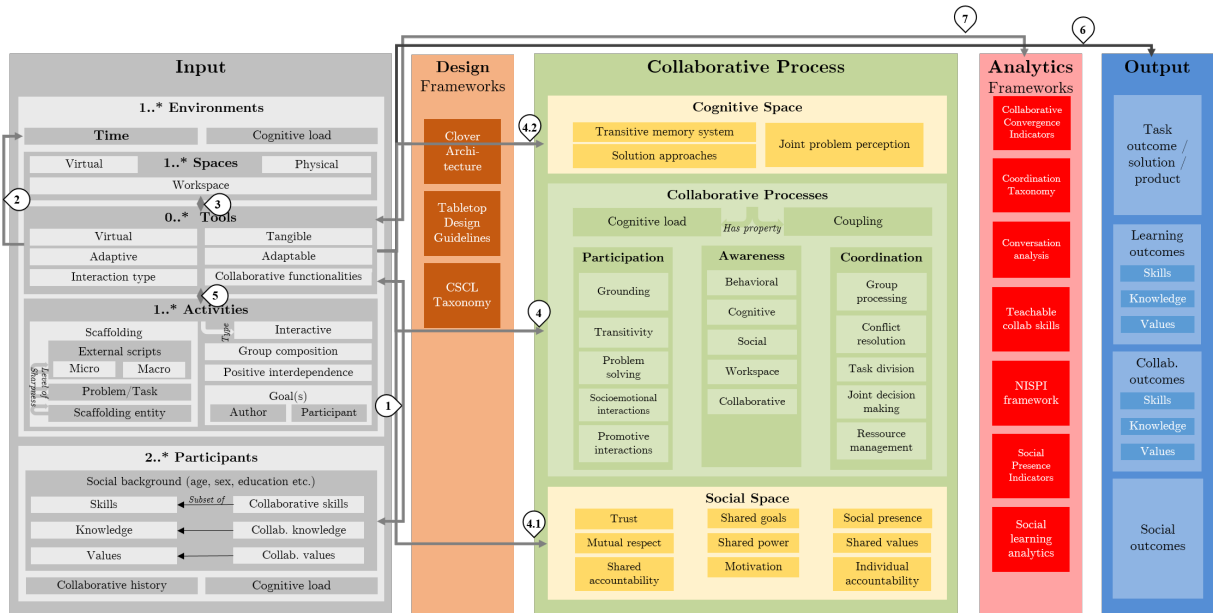


Figure 2.18: Extended PAC Framework with tool links

and (1.2)). The activity might particularly scaffold a certain aspect within each of them, for example establish roles to assist resource management (like a timekeeper), provide a “wicked” problem to strengthen the joint problem space or external scripts to assist with particular collaborative processes that group members can use (4). Participants might entertain existing relationships with other group members (6), which has an impact on the social space (e.g. existing trust and motivation) (6.1).

Participants take on roles defined by the activity, possibly resulting from defined positive interdependence (2). P. A. Kirschner *et al.* (2018) noticed that for group members to engage in collaborative activities, the cognitive load must be higher than what a group member can handle on their own to make transactive costs of collaboration an interesting problem solving strategy. This means, that participants might engage in an estimation of the cognitive load associated to the problem or task of the activity (3). Finally, their collaborative history determines their collaborative skills, possibly also collaborative knowledge and collaborative values.

Linking Collaborative Processes and Analytic Frameworks

Figure 2.20 shows the links between collaborative processes themselves and analytic frameworks. Among the collaborative processes, awareness is widely acknowledged to be funda-

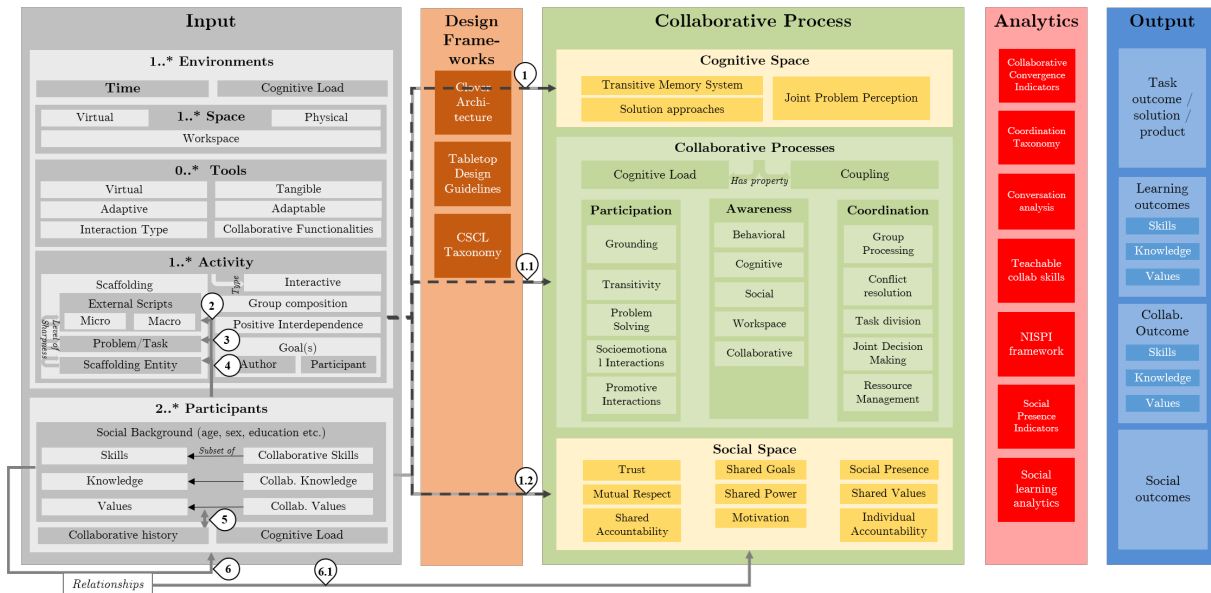


Figure 2.19: Extended PAC Framework with Activity and Participant links

mental for collaboration and collaborative learning. Behavioral awareness is a prerequisite for transactive interactions: Without knowledge what other group members are doing, one cannot refer to their actions and build on them. Similarly, to successfully engage in negotiation of conversational turns, members must analyze and act on the right cues (1). Cognitive awareness is the foundation for a functional transactive memory system (2). Social awareness is what is required to engage in perspective-taking for establishing collaborative values such as mutual respect and trust (3). Beyond the previously described types of social, behavioral, cognitive and workspace (4) awareness processes, awareness on collaborative processes has been identified, allowing group members to reflect on their emotional and cognitive states and alter them accordingly (5) (Cress *et al.* 2021).

Coordinative processes can occur in the cognitive space in the form of strategies to solve a problem or accomplish a task, or in the form of meta-strategies (group processing) monitoring and altering solution strategies depending on their perceived performance (6). Coordinative processes are also required to channel contributions to the social space. Conflict resolution (7) is essential to reduce frustration and maintain motivation. It refers to both social and cognitive conflicts in the JPS (joint problem space). The notion of social presence is still debated (Weidlich *et al.* 2018) but broadly describes the peer’s perception of a member within a group through their communicative activities. We hypothesize that socioemotional interactions (14) are one component of social presence among others,

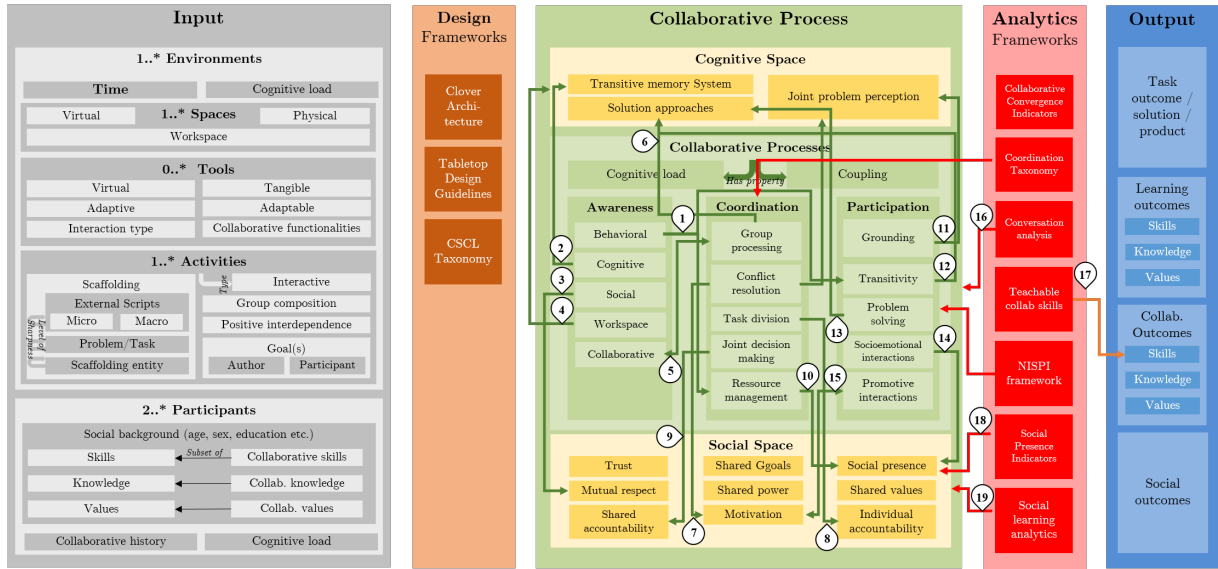


Figure 2.20: Extended PAC Framework process links and analytics frameworks

such as resource management (10). Balanced resource distribution allows for participation of more hesitant group members, thus increasing their social presence. Kreijns *et al.* (2013) similarly stated that through participation, members build their social visibility in a group. The concept might thus not only be applied to online but also collocated settings. Bachour *et al.* (2010) have shown the positive impact on mirroring tools showing the group participation of group members and highlighting the importance of a balanced participation for collaboration in this context. Griffiths *et al.* (2021) propose a hierarchical structure of collaborative processes for the social space: the foundational relations are built on communication and trust, which enables negotiation for shared values, which in turn encompass shared goals and common understanding. Once this step is taken, team members show active engagement by sharing responsibilities and active participation. Finally, collaboration takes place when decisions are taken and negotiated collectively (*ibid.*). While the serial nature of this perspective is problematic since the processes of active engagement have been observed to occur in parallel to the construction of shared values and relationship building (Kreijns *et al.* 2013), it provides a structure of the social space and the links between its properties. Grounding is the process of establishing shared meaning and thus constitutes a key part for the creation of a joint problem space (11). Grounding interactions include clarification requests, repair requests, acknowledging, summarizing and agreement verification (Baker *et al.* 1999). Researchers also highlight the importance of transactive communication in this context. Transactive communication

⑫ refers to group members mutually building on previous contributions. By doing so, groups can conjointly develop solutions in the solution space. Similarly, problem solving ⑬ is an umbrella term for different actions in the JPS and solution space: generating and discussing predictions of outcomes for solutions to collectively build a solution and validation strategy. Communication can also focus on the social space to motivate each other ⑮ (D. W. Johnson and R. T. Johnson (2004); Vogel *et al.* (2017)). ⑮ depicts the bilateral relation of motivation and promotive interaction. We can hypothesize with observations of P. A. Kirschner *et al.* (2018) about collaborative script imitation, that the use of promotive interactions and resulting positive motivational patterns may in turn influence the behavior and use of such interactions.

In terms of analytical frameworks, Cukurova *et al.* (2018) have established gestural indicators for detecting successful collaboration through the alignment and symmetry of gestures in their NISPI framework. Conversation analysis is a widespread tool to analyze collaborative discourse and detect conflicts or problems of communication ⑯. Hesse *et al.* (2015) have established an extensive list of collaborative skills and relevant indicators to assess those skills. Those indicators can be conveniently associated to the components of the presented framework ⑰. Other frameworks target specific processes or components of the collaborative process. For instance, Weidlich *et al.* (2018) have identified a 10 item indicator to measure social presence. As Weidlich *et al.* note, there are many frameworks on how to measure social presence. A comparison of the existing analytic frameworks to a same concept seems like yet another interesting perspective, although beyond the scope of this dissertation.

2.3 Conclusion on the PAC Framework Proposition

In this chapter, we have presented the PAC framework and the methods we have employed to create a core and an extended version of it. The **Core PAC Framework** is based on an **input-process-output** structure that has emerged from the previous chapter. We detailed the Process part through a comparison of four key frameworks in the field, each contributing different and overlapping aspects to three process categories: **Participation, Awareness and Coordination**. We then extended this core of processes with a **Cognitive** and a **Social Space**, both key concepts of CSCL. We detailed collaborative input by the concepts of **environment** of the **activity** and the **participants** involved in the activity, each with **collaborative skills/knowledge and values**. We then distinguished

four collaborative outputs: **Task, learning, collaborative and social outcomes**.

The **Core PAC framework** will be used in the next parts of this manuscript. In the next part, it will be used to map collaborative tool functionalities to the three main collaborative process categories (Participation, Awareness and Coordination). In the fourth part of the dissertation, it will offer the conceptual ground for the experiments we conducted on the effectiveness of the tools we propose.

The **Extended PAC framework** is based on the Core PAC framework. It details collaborative processes, input and output through a literature review on frameworks (mainly CSCL but also CSCW and others) presented in 2.2.1. The results draw on 42 frameworks retained in the selection process. Beyond detailing the process categories (PAC) through explicit processes, the different processes have been linked to each other and to the different input conditions. We have further integrated collaborative analytics in this framework, listing different analytical frameworks with different foci. We further analyzed the role of design frameworks for their usage to support the design of collaborative learning tools. Its acceptance as a long paper at the ISLS/CSCL 2024 conference further reinforces its credibility. The framework proved a versatile tool to effectively describe the diverse circumstances and benefits that collaboration can offer.

This chapter presented an extended vision of collaboration that we detailed as much as possible within the limits of time and resources of this PhD. The final **joint PAC framework** we propose cannot pretend neither on completeness nor universal applicability. The latter is due to the highly contextual nature of each of the cited studies. For instance, the generic links between concepts are founded in studies in literature, but even frameworks in literature do not present systematic and conclusive data for universal applicability. This is precisely one of the use cases we intend this framework for: members of the CSCL community can use it to **document** their research hypothesis, experiment and findings through detailing links between collaborative processes and environmental parameters (as will be exemplified in the third part of this dissertation), increasing the weight of similar findings. From this point of view, the framework follows and extends Rummel (2018) effort to provide a common framing for the design of CSCL support, but also experiments. Adoption and use of the extended PAC framework for the documentation of the design of CSCL experiences in a form or submission tool could improve and facilitate comparability. The different results, once centralized, can be “overlaid” and existing links in the dataset either strengthened or challenged by the new results to update the existing framework. For such an endeavor to succeed, the proposed frame-

work requires an extension to also document the scientific method used for the findings obtained. The visual dimension of connections for instance could reflect confirmation, contradiction or creation of connections between concepts depending on findings from different studies. The studies being documented through a common template, such cognitive conflicts can foster discussion and further collaboration among CSCL researchers or provide new research questions for other researchers. As showcases the necessary division into five different illustrations (figure 2.15 - 2.8) in this section, the visualization does not scale well in terms of readability and understandability. The complexity not only of the phenomenon of collaboration, but also of finding an adequate visualization is obvious and another limitation of this work. For instance, we have detailed internal and external scripts through F. Fischer *et al.* (2013)'s model in this work as well as D. W. Johnson and R. T. Johnson (2009) taxonomy of promotive interactions, yet it appears difficult to integrate this level of detail into the current visualization.

SUMMARY ON DEFINITIONS AND FRAMEWORKS

In this conceptual part, we have presented our vision of collaboration, grounded in an analysis of both a definition of CSCL and a two stage framework that builds on this definition. Having started from an approach of decomposition of the different CSCL concepts, **we defined computer support, collaborative learning, learning and collaboration** in order to find a CSCL definition.

The **Core PAC Framework** is grounded in the definition of collaboration as a process. We built on the input-process-output structure by comparing four frameworks of collaboration to extract shared dimensions (Participation, Awareness and Coordination), before introducing Cognitive and Social space and detailing Output and Input. The Core PAC Framework presents an overall vision of collaboration and its different contexts that we distinguish by the output of the collaborative process. In the next part, this framework will see application in a meta-analysis. In part four, we will highlight its use in the conceptual underpinnings of our experiments.

The **Extended PAC Framework** has been obtained through a literature review on frameworks. It integrates studies and findings on specific topics into the first Core PAC framework and further details both its components beyond the collaborative process categories, as well as input and output. We also integrated the dimension of tool design to improve, and analytics frameworks to analyze collaboration. The result is a detailed vision of the current research on collaboration, meant as a potential artefact for the CSCL community. In the context of this dissertation, it will serve as a map on which we locate the remaining contributions. It can be observed that albeit the many aspects of the extended PAC framework, all elements of the definition of collaboration as a set of collective processes in which two or more entities engage in a joint effort towards a common goal by establishing common ground, still can be found in this detailed vision. The following parts of the dissertation will draw on those conceptual visions and showcase the use of the elaborated frameworks.

PART II

Collaborative Software

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CONTEXT

Since the advent of technology enabling large, interactive touchscreens, the latter, among other collaborative tools, have been the subject of extensive research for small collaborative group learning in lab and classroom settings (Martinez-Maldonado *et al.* 2013). While many of those studies have shown a positive impact of such tools on collaboration through effect oriented research, it is not clear which tool functionality fosters and supports which aspects of collaboration and in which way. This is due to a variety of reasons. Firstly, tools developed for research experiments offer a multitude of functionalities (J. Liu *et al.* 2015). Studies also differ between each other in terms of tool and activity design, making cross-study comparisons very difficult.

One example of such a functionality-rich tool is Caretta, developed by Sugimoto *et al.* (2004). Caretta is a city planning application where students must integrate new infrastructure into an existing urban planning scenario. The tool comprises several **functionalities**: a shared digital table supporting parallel input, personal devices for individual work, tangible tokens to increase awareness on user interactions (workspace awareness), and voting mechanisms to facilitate collective decision making (*ibid.*). It is interesting to note that the addition of voting mechanisms was necessary because the other functionalities did not lead to meaningful collaboration. However, this does not imply that functionalities like parallel input are irrelevant for collaboration (as will be demonstrated in this dissertation). Instead, it highlights the intricate relationship between tool functionalities, collaboration, and activity design.

Investigating the Role of Functionalities

Tool designers wish to make informed decisions on what functionality to integrate at what point in their system. In the remaining parts of this dissertation, we will present two studies for which we have taken on this role. This implies knowing what functionality supports which aspect of collaboration to which degree (its impact on one or multiple collaborative processes) and how multiple functionalities should be combined to achieve optimal support, for a given context (activity, environment, participants). The extended PAC

framework, presented in the previous part, integrates two design frameworks, intended to inform tool design. However, these frameworks do not specify which functionality to deploy for which aspect of collaboration. S. D. Scott *et al.* (2003) for instance, have elaborated general guidelines and functionality to assist collaboration instead (e.g. the use of physical access objects). In the previous part, we thus established a joint vision of collaboration from literature. Thereby, we have endowed ourselves with a tool to now analyze software functionalities concerning their impact on collaboration and collaborative learning in the second chapter of this part.

The objective is not only to identify functionalities to facilitate collaborative processes, but to guide student's mental effort to learning processes. If the focus is a learning outcome, it is desirable that mental effort is focused on the exchange and negotiation of domain knowledge. If the focus lies on the learning of collaboration, mental effort should be guided towards collaborative processes. Tools can make those processes visible and through their disposition, engage learners in these processes.

Structure

In chapter 3, we will identify potentially collaborative functionalities that have been used in studies on collaboration (CSCW and CSCL). With this list, we will attempt a meta-analysis on their respective collaboration impact, based on results in literature in chapter 4.

Related Publications

Simon, S., Marfisi-Schottman, I., George, S. (06/2023). Towards Linking Tool Functionalities to Processes of Collaborative Learning. In *Proceedings of the 16th International Conference on Computer-Supported Collaborative Learning-CSCL 2023*. International Society of the Learning Sciences. Montréal, Canada. p. 205-208.

COLLABORATIVE FUNCTIONALITIES

Designing interfaces and affordances that offer ergonomic access to virtual spaces has long been a challenge. Single-user interfaces alone present difficulties in achieving optimal design, but the complexity increases with multi-user interfaces, a domain that has only been extensively explored in the past two decades, particularly in online environments. Moreover, multi-user interfaces have not been addressed at the same scale as single-user interfaces, adding an additional layer of complexity to the design process. Building collaborative tools requires a considerable amount of resources. In the research context, innovative tools oftentimes are not followed by long term or large scale user studies which would allow a more detailed analysis of how the different functionalities act on collaborative processes. Commercially successful collaboration tools like Google Office in turn, do not disclose data about the collaborative behavior of their users. Efforts, within the CSCL community, to provide guidelines for collaborative software have been made early on, such as S. D. Scott *et al.* (*ibid.*)’s design guidelines. However, recent research studies have not extensively pursued this objective. We hypothesize that this might be due to the fact that a shift to a process-oriented research in CSCL and a focus on the functionality level has occurred only in the last decade, and that it is difficult to generalize in greater detail due to the aforementioned small user studies around each developed tool. For designers who wish to design collaborative tools, it would be ideal to have, at their disposal, a curated list of collaborative functionalities that have demonstrated effectiveness for collaboration and CSCL, based on research findings in various environments.

3.1 Method

The most prominent collaborative hardware device for in-person collaboration that we are aware of, in CSCL research, is the **interactive tabletop**. We therefore focus on this device for establishing a first list of collaborative functionalities, drawing on contributions from CSCW, CSCL and HCI.

We analyzed various studies on collaboration around interactive tabletops in an initial exploratory literature review, drawing from sources like the *International Handbook of*

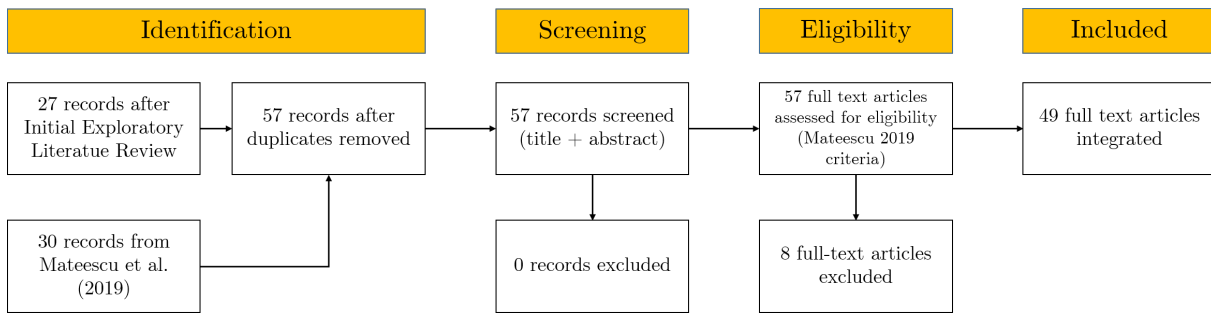


Figure 3.1: Collaborative functionality literature review method

International Learning Sciences (Cress et al., 2021), as well as other journal articles (see figure 3.1).

We identified 20 recurrent tool functionalities, as defined in Simon *et al.* (2022b), in those studies. In order to obtain a high quality corpus of studies, we examined 30 contributions that Mateescu *et al.* (2019) selected in their systemic review (12/2019) of more than 1400 contributions on collaborative tools. Papers that related to collaboration around interactive tabletops and met eligibility criteria such as “sound experimental methodology” (if authors provided information about the method used, sample size and statistical details) and screening criteria (article length above 10 pages, English language etc.) were selected.

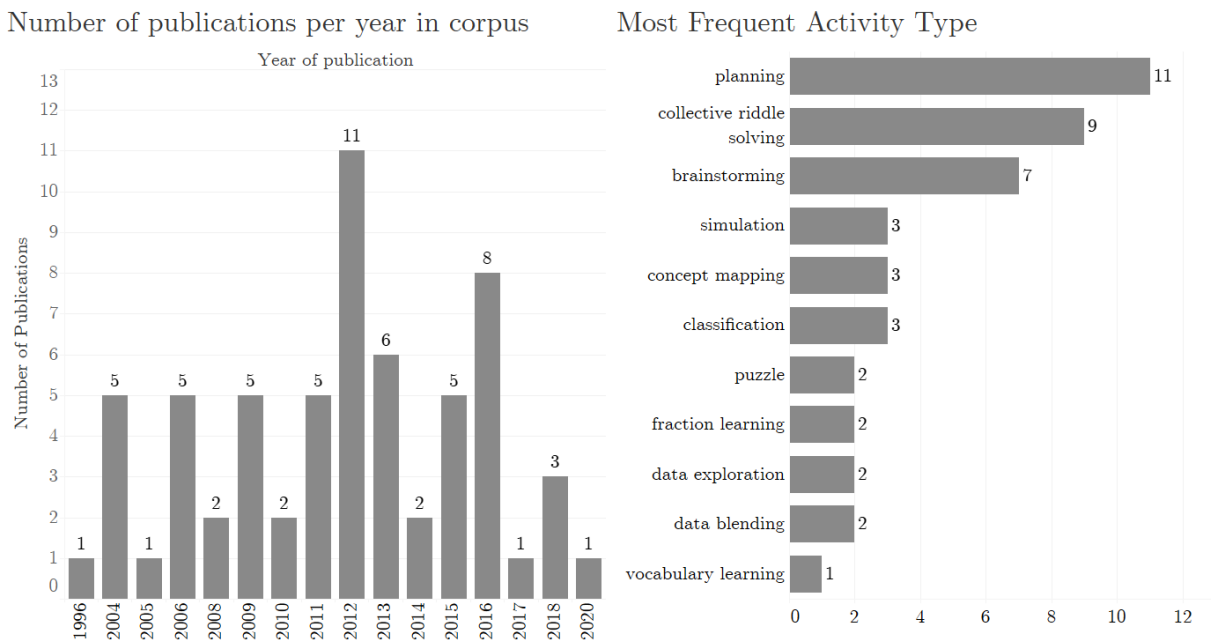


Figure 3.2: Corpus publication year and activity type statistics

Additionally, we included papers from our initial exploratory study that met Mateescu *et al.* (*ibid.*)'s eligibility criteria but were filtered due to the screening criterion of being longer than 10 pages. We included these studies because work on isolated tool functionalities often fits within 8 pages. The functionalities identified in our initial exploratory study reappeared throughout the works identified by Mateescu *et al.* Overall, the final corpus of studies includes 49 papers, published between 1996 and 2020. Half of the studies have been published after 2012. Reported activity types are predominantly activities of planning, collective problem solving and brainstorming (see figure 3.2).

3.2 Results

In total, we identified **20 collaborative functionalities** that recurred (in varying frequencies) across 49 studies of tools. Furthermore, we grouped these functionalities as follows in table 3.1:

1. **Artefact manipulation** (functionalities 1-5): These functionalities involve manipulation of digital artifacts, such as visual sorting and filtering.
2. **Input methods** (functionalities 6-8): This group includes functionalities related to different input methods used in collaborative activities.
3. **Mirroring tools** (functionalities 9-11): These functionalities, as coined by Mateescu *et al.* (*ibid.*), provide users (or educators) with feedback on their actions during collaboration.
4. **Metaprocess manipulation** (functionalities 12-16): This group encompasses functionalities for manipulating the process of collaboration, including planning, structuring the activity, or enforcing activity design.
5. **Territoriality** (functionalities 17-19): These functionalities support the establishment and management of territorial spaces during collaboration.
6. **Playfulness for participation** (functionality 20): This functionality encourages participation through playful elements integrated into collaborative activities.

In the following sections, we detail these groups through the individual functionalities, listed in table 3.1.





















Number	Group	Tool Functionality	Occurrences in corpus
1	Input Methods	 User Embodiment	1
2		 parallel input	36
3		 tangible tokens	6
4	Territoriality	 dynamic territoriality	4
5		 static territoriality	8
6		 shared and individual devices	5
7	Mirroring Functionalities	 educator awareness tools	1
8		 participation feedback	3
9		 movement traces	2
10	Metaprocess Manipulation	 orchestration tools	5
11		 process building	2
12		 voting mechanisms	1
13		 activity enforcement	6
14		 scripting	1
15	Playfulness	 physics engine	1
16	Artefact Manipulation	 sorting artefacts	2
17		 resizing artefacts	6
18		 grouping artefacts	6
19		 problem decomposition	2
20		 tool bridging	4

Table 3.1: Identified collaborative functionalities in experimental tools. Credits for icons: flaticon.com

3.2.1 Input Methods

Among the identified functionalities, **parallel input** emerges as the most frequently used functionality, occurring 36 times in 49 tools. With the advent of commercially available large touchscreens, implementing parallel input no longer requires additional effort from a hardware perspective. Additionally, hardware typically comes with software development kits, further simplifying implementation. Nevertheless, its importance for collaboration cannot be neglected: Before the widespread use of touchscreens, researchers had to develop their own hardware (Sanneblad and Holmquist 2006) oftentimes based on digital

pens that were able to determine their position on the tabletop. Interestingly, in several studies, the number of these entry points was often fewer than the number of participants. The pens had to be shared among group members. Nonetheless, turn-taking was rarely observed: one participant, holding the device, would monopolize it and other group members would simply restrain themselves to providing suggestions (Y. Rogers and Lindley 2004). Similar observations have been made in other studies in control conditions with one computer and one mouse input. Conversely, this behavior has not been present with two mice on the same computer (Shaer *et al.* 2011). Shaer *et al.*'s study is also of interest since it highlights the necessity to not only provide parallel input possibilities hardware - but also software wise. Today, the majority of operating systems are not built around a concurrent collocated multi-user policy and Shaer *et al.* observed the limits of just two computer mice in various conflict situations that had to be resolved when users executed conflicting actions on the computer. This leads us to believe that parallel input functionality, independently of the type of device (direct touch, mouse, digital pen), benefits collaboration but requires implementation in both soft- and hardware. Morris *et al.* (2006) report first insights on such software features to mitigate problems resulting from concurrent access to virtual artefacts through "coordination policies": A document automatically duplicates when two users try to move it into their personal space on a tabletop, the use of hierarchy implemented in the software (higher ranking users can take documents from lower ranking users) and global changes need to be confirmed by all users. Morris *et al.* (*ibid.*) implemented voting mechanisms to support the latter. It is evidence for how different functionalities can support conjointly (here: parallel input and voting mechanisms) collaboration.

Tangible tokens are alternative entry points (Kirsh (2001), Yvonne Rogers *et al.* (2009)) to virtual spaces (figure 3.3). The idea of providing tangible entry points to interact with virtual objects has grown into a subdomain of human-computer-interaction since the publication of the paper *Tangible bits: towards seamless interfaces between people, bits and atoms* by Ishii and Ullmer (1997). The use of these tokens has been a more recent tendency. Yvonne Rogers *et al.* (2009) hypothesize that, "if there are particular participants who find it hard to talk (e.g., nonnative speakers and children with learning difficulties), then entry points designed to be highly tangible and accessible may encourage them to participate more in nonverbal ways". Jetter *et al.* (2011) noticed the benefits of tangible tokens for increased participant's awareness in their experiments and their role as a memory help for past processes. Participants in their study remembered who had

interacted with which virtual artefact thanks to physical tokens on an interactive tabletop. Another input related functionality is virtual **user embodiment**, a representation of



Figure 3.3: An example of the use of tangible tokens on an interactive tabletop: when in contact with the surface, the token becomes a controller to manipulate the virtual space (George *et al.* 2017)

the user within virtual space (Benford *et al.* 1995). Virtual user embodiment not only determines how other users of a system perceive a user, but also the way the user can interact with the virtual space. Physical embodiments in turn “make use of the actual physical body of the user” and “use direct touch” (using hands, pens, or tangible blocks). For example, techniques such as pick-and-drop (S. Scott *et al.* 2014), drag-and-drop, and media blocks (Ullmer *et al.* 1998) do not require virtual embodiment because the user’s body and tools allow others to track their actions. One of Pinelle *et al.* (2008)’s study results consist of the participant’s preference for virtual embodiment techniques over a physical embodiment around an interactive table. The embodiments were introduced to allow participants access objects across an interactive table out of their physical reach. Users were also much more likely to make use of the whole table and reach in otherwise inaccessible areas.

3.2.2 Territoriality

The second most used functionality group, **territoriality** (comprising both static and dynamic aspects), involves attributing screen space to a particular user.

Static territoriality, where territory is assigned beforehand to a user, is mainly observed in studies testing other functionalities, such as user embodiment through virtual gestures (giving users attributed space on the table for the gestures to control the embodiment). Territoriality was extensively analyzed by Klinkhammer *et al.* (2018) who discovered that users dynamically allocate space when given the choice, and that these **dynamic territories** are part of a coordinated effort to construct a common vision of a problem or activity. In instances where no fixed zones are apparent initially, there seems to be a phase where participants naturally take ownership of a part of the screen (*ibid.*). S. D. Scott *et al.* (2004) identified three types of territory: personal, group, and storage territory. Personal territory, in particular, appears to foster the creation of a personal problem space: at the beginning of an activity, participants utilize personal territory to organize and analyze their ideas and knowledge concerning the topic. This behavior has been observed across different activities such as urban planning and brainstorming, in various studies (Klinkhammer *et al.* (2018), Hilliges *et al.* (2007), Clayphan *et al.* (2014), Homaeian *et al.* (2018)).

The presence of **shared and individual devices** introduces a unique aspect of territoriality, where private space can be integrated into the physical privacy of the participant and carried around. This feature has led to observable differences in physical behavior, as demonstrated in the study conducted by Klinkhammer *et al.* (2018): when provided with tablets in addition to a shared tabletop, participants often ended up working side by side on the given brainstorming task. In contrast, integrated personal space on the tabletop led to a static face-to-face configuration. This suggests that shared devices allow participants to choose their preferred configuration, adapting the tools provided to their preferred workstyle rather than having to adapt their workstyle to the tool. However, it is worth noting that this effect might be partly due to a physical limitation of interactive tabletops: writing cannot be read as easily from the opposing side as from the side it is facing. Another finding by Klinkhammer *et al.* (*ibid.*) was that communication and coordination were improved in the individual device configuration. Since this study was the only one in our corpus comparing both configurations, further research is needed to consolidate these advantages and determine the appropriate conditions for territoriality to positively impact collaboration. Finally, Sugimoto *et al.* (2004) observed that the mere

presence of individual devices, to complement a shared space, does not guarantee enhanced collaboration; participants tended to exclusively work on their individual devices rather than collaborate on the shared screen in their urban planning scenario. This underscores the importance of integrating territoriality into activity design to encourage collaboration effectively.

3.2.3 Mirroring Functionality

Just like territoriality, **participation feedback** can support accountability, a condition for collaboration. Clayphan *et al.* (2014) provided statistics to the users at the end of each activity stage to assess the number of their contributions (figure 3.4). Bachour *et al.* (2010) developed a visualization representing the time of discourse by participant in real time during a crime-solving activity. This resulted in a significant reduction in contributions from "over-participants" when provided with participation feedback.

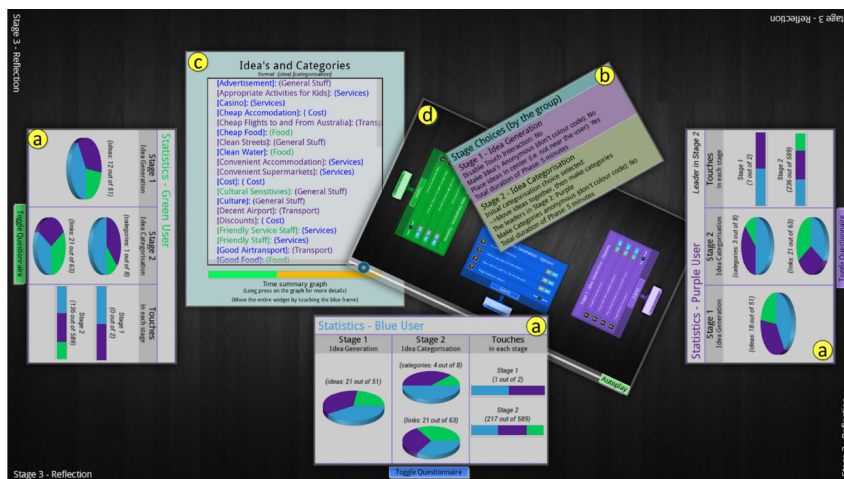


Figure 3.4: Participation feedback on an interactive tabletop after a brainstorming activity (Clayphan *et al.* 2014)

However, Yvonne Rogers *et al.* (2009) noted that visual feedback does not necessarily encourage under-participants to contribute more; they "tend not to increase verbal contribution when given awareness visualizations." It seems that visual feedback primarily impacts over-participants, thereby also improving self-regulation. Consequently, if such a functionality were to be implemented, particularly on personal devices, it may be targeted at over-participants (e.g. displaying a widget on their personal devices or spaces when a disequilibrium appears in conversations or participatory actions. In the CSCL context,

this presents a learning opportunity to improve learners' metacognition. More fine grained dashboards may additionally foster self-monitoring and -judgement of group members (Michel *et al.* 2012).

Other functionalities, like **educator awareness tools**, that also can be considered mirroring tools, as coined by Mateescu *et al.* (2019), provide real time feedback to teachers about student progress. These tools have been found to increase classroom awareness among teachers, leading to improved collaborative scaffolding and learning outcomes for groups (Martinez-Maldonado *et al.* 2014).

We also clustered the functionality **movement traces** in this category. Movement traces are a feature that help participants understand what other group members do. This functionality was implemented for instance by Shadiev *et al.* (2015) in a tabletop study on group awareness strategies through an animation when a virtual object was transferred from one location to another.

3.2.4 Metaprocess Manipulation

The group we named Metaprocess Manipulation encompasses functionalities designed to help groups better organize their collaborative processes (figure 3.4). Examples include visualization tools for problem-solving strategies (such as those discussed by Nussbaumer *et al.*, 2012), scripting functionalities, voting mechanisms, as well as tools for educators to adapt scaffolding and intervene when help in collaboration is required (orchestration tools).

An example of the latter type of tool is MTDashboard, developed by Martinez-Maldonado *et al.* (2013), which informs teachers about progress and actions (Mirroring tool) in group work around interactive tabletops in classrooms. Not only is MTDashboard a mirroring tool, the teacher can also scaffold the activity from a distance: A tablet interface allows to remotely control the tabletops (start and end the activity, freeze tabletops or reset the workspace) In contrast, Clayphan *et al.* (2014) designed a tool for a brainstorming activity where group members could negotiate the parameters of the group activity, such as enabling/disabling interfaces or color coding virtual objects and thus script their activity. Such **Scripting** can be either positive or negative. Negative scripting creates socio-cognitive conflicts (for example by the intervention of a teacher with a question highlighting student's faulty conclusions) while positive scripting aims to scaffold collaborative processes. **Voting mechanisms**, for instance, can be configured to be used when a common decision is required, fostering discussion and exchange (Sugimoto *et al.*

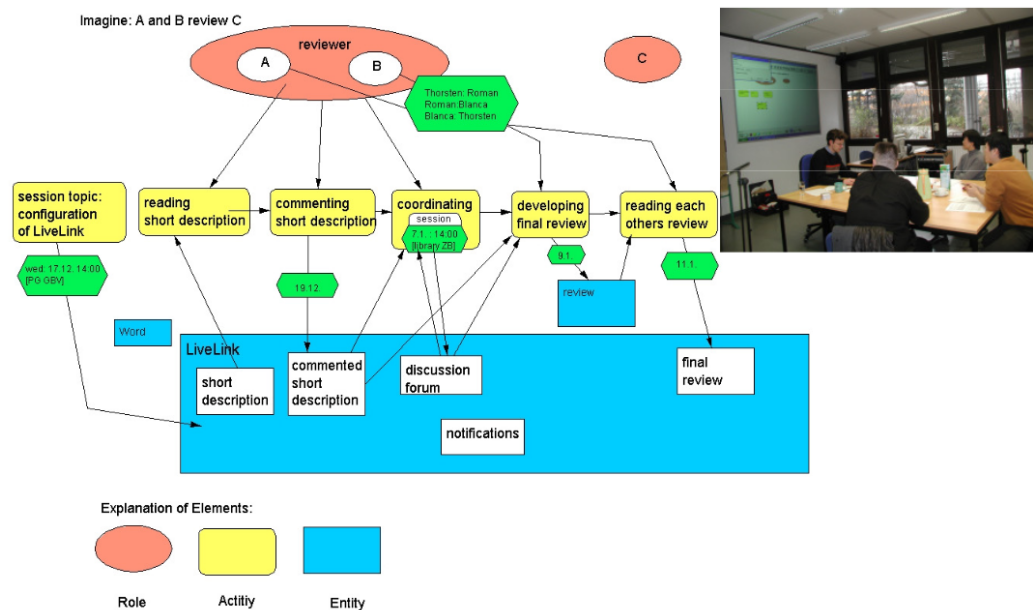


Figure 3.5: Process building tool by Carell *et al.* (2005)

2004). Process building tools, as illustrated in figure 5, help plan activities and structure the flow of an activity. Carell *et al.* (2005) for instance have designed a tool to support and document the roles in a task of collaborative writing: the group could design and visualize the different interdependencies between their tasks and the overall procedure they negotiated. The interest of such tools lies as a support for group processing (the analysis and adaption of strategies). We named **activity enforcement** tool functionality that enforces properties of the activity design. Maquil *et al.* (2021) for instance designed a collaborative game on the exploration of mars with a rover. Controlling the rover required all members to interact with the controls simultaneously, enforcing positive interdependence. The use of tools to structure and influence the underlying collaborative process is particularly interesting for CSCL scenarios, since these functionalities guide group members in their collaborative actions and encourage groups to collaborate through the use of the tool, fostering the need for coordination and negotiation.

3.2.5 Playfulness

Pinelle *et al.* (2008)'s user embodiment study revealed a notable side effect: playfulness. Buisine *et al.* (2012) explicitly measured the pleasantness of group work in a study involv-

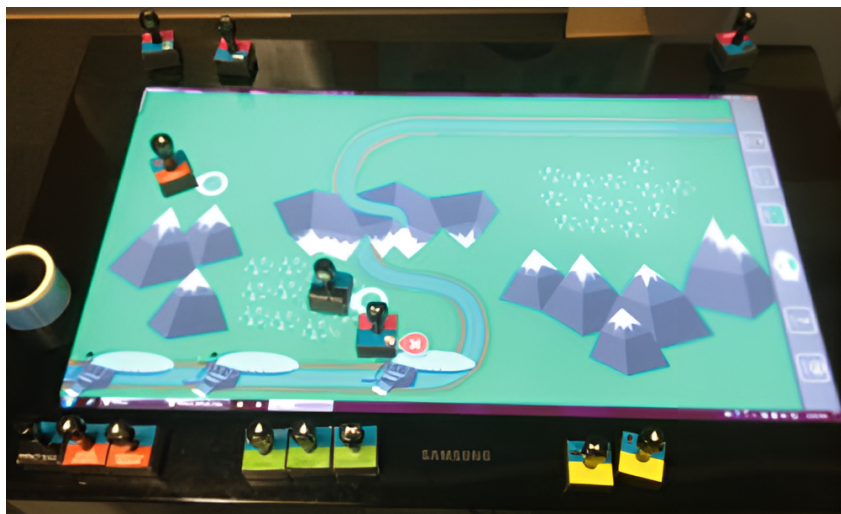


Figure 3.6: Interfaces with playfulness to foster collaboration. Antle (2014)

ing a groupware interface that enabled users to interact with a physics engine, allowing virtual artifacts to be sent across the table to other users. The incorporation of playful elements into collaborative tools, often achieved through gamified elements, has received attention in CSCL research in recent years for its potential to foster collaborative learning (Garcia-Sanjuan *et al.* 2018). This focus highlights the recognition of playfulness as not only an enjoyable aspect but also as a valuable facilitator of engagement and learning within collaborative settings. Figure 3.6 shows another instance of playfulness implemented through functionality enabling the design of a customized world in an environment simulation game. Gamification of interactions has indeed been identified as a promising way to engage learners in collaboration (Riar *et al.* 2022).

3.2.6 Artefact Manipulation

The group **Artefact manipulation** encompasses functionalities related to virtual objects, including **grouping**, **resizing**, **rotation**, and **sorting**. While these functionalities may seem trivial, they can play a crucial role in facilitating collaboration. For example, resizing an artefact has been shown to positively impact group awareness and aid in the prioritization of clues in tasks such as investigating the origins of a mining accident in a history task (Higgins *et al.* 2011).

Tool bridging is another feature within this group that helps mitigate the extraneous cognitive load (cognitive load unrelated to learning processes occurring through the use of

tools etc.) related to the task itself, allowing students to dedicate their cognitive resources to collaborative processes. This functionality involves actions in one tool impacting another. For instance, G-surfer, an application for genomics learning, allows the selection of an anatomical part to open a detailed tissue visualization tool for the selected area (Shaer *et al.* 2011), thereby reducing the manual lookup work required by the user.

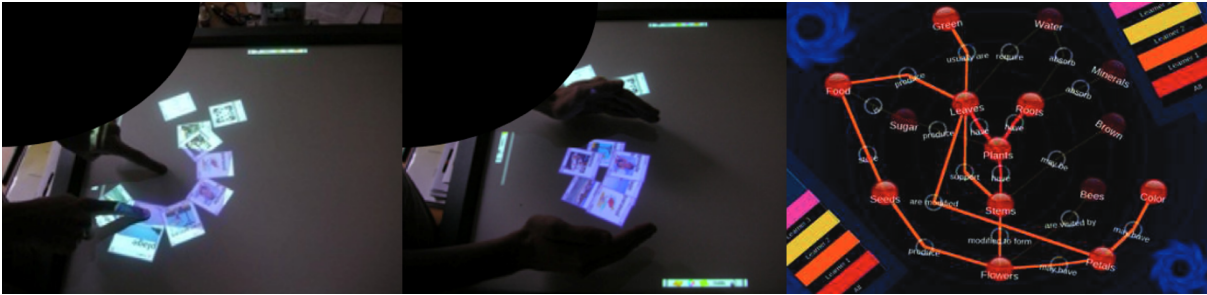


Figure 3.7: Examples of Artefact Manipulation functionality (left to right): sorting, grouping, comparing (Buisine *et al.* (2012), Martínez Maldonado *et al.* (2010)

Functionalities supporting **problem decomposition** provide scaffolding for better management of related sub-problems. For instance, Martínez Maldonado *et al.* (2010) designed a tool for the creation of collaborative and individual concept maps, providing visual affordances to compare each individual’s vision and scaffold negotiation of common ground. This decomposition helps address the challenge of finding common ground by breaking it down into manageable sub-problems related to negotiating individual visions with the group vision.

3.3 Framework Contribution

The 20 identified functionalities, presented above, offer more detail to the PAC framework presented in Part I, which describes tools as entities with tangible and/or virtual properties. In line with this framework, we classified all functionalities as either virtual, tangible, or both, represented by gradient color in figure 3.8 and added the element “collaborative functionalities” to the PAC Framework. This classification helps provide a comprehensive understanding of how these functionalities contribute to collaborative processes and how they interact with the physical and digital aspects of collaborative tools.

The distinction between purely virtual functionalities and those that could be enacted with minor effort without computer support provides another layer of understanding to the framework. Purely virtual functionalities require dedicated computer support for

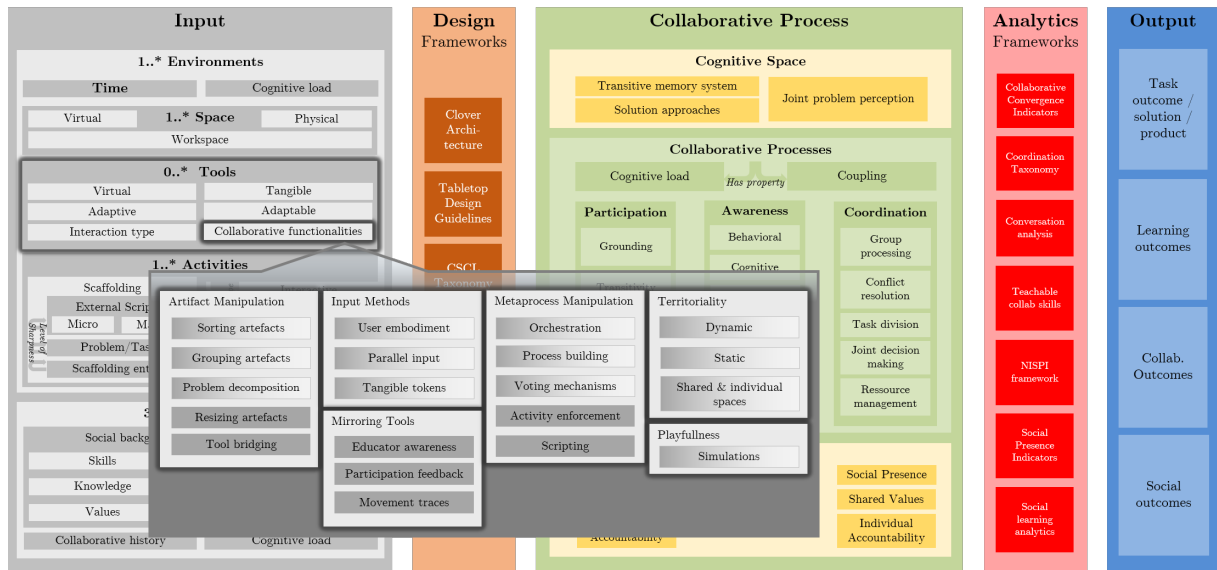


Figure 3.8: Extension of the Input element "tools" of the extended PAC Framework. Dark gray: exclusively software based, light gray: tangible implementation possible

their execution, implying that without such support, these functionalities would either be impractical or more labor-intensive to implement. On the other hand, tangible or hybrid functionalities like voting can be implemented with minor effort even without computer support.

This distinction opens up another potential use case for the design of learning activities. By integrating links to collaborative processes, designers can specifically choose functionalities to support specific aspects of collaboration. Moreover, they can decide whether these functionalities should be implemented physically, virtually, or in a hybrid manner, depending on the context and desired outcomes of the learning activity. This flexibility allows for tailored design choices that align with the collaborative needs and objectives of the learning environment.

3.4 Conclusion on Collaborative Functionalities

In this chapter, we identified **20 functionalities** across a **corpus of 49 studies**, grouping them into **six categories**. This list provides a comprehensive overview of functionalities that directly support collaborative processes as well as those that indirectly support collaboration by reducing task-related cognitive load. This contribution extends the Input part of the PAC Framework. Our motivation, in the next chapter, spurred by our in-

tention to design collaborative tools, will be to explore how these functionalities impact collaborative processes (and by consequence their potential for collaborative learning). By understanding the impact, we aim to inform the design and implementation of collaborative tools that effectively enhance collaborative processes and outputs.

MAPPING FUNCTIONALITIES TO PROCESSES

In the previous chapter, we have identified 20 recurrent functionalities in collaborative tools and in the previous part of this dissertation we established a common conceptual PAC Framework for collaborative processes. In this chapter, we combine both of these by **mapping tool functionalities to conceptual collaborative processes**, based on evidence provided by the corpus of 49 studies. The resulting mapping between tool functionalities and collaborative processes, presented in this chapter, is a first step towards a finer grained vision of how tools affect collaboration.

4.1 Challenges

As detailed in the previous chapter, our analysis of the 49 studies shows that almost all of them do not detail or use non-standardized vocabulary of the examined concepts. Furthermore, we noticed a tendency towards a holistic analysis, in the sense that researchers usually attempted to establish a link between collaboration and their tool, as a whole, without examining the impacts of its specific software functionalities. Finally, as retrieved

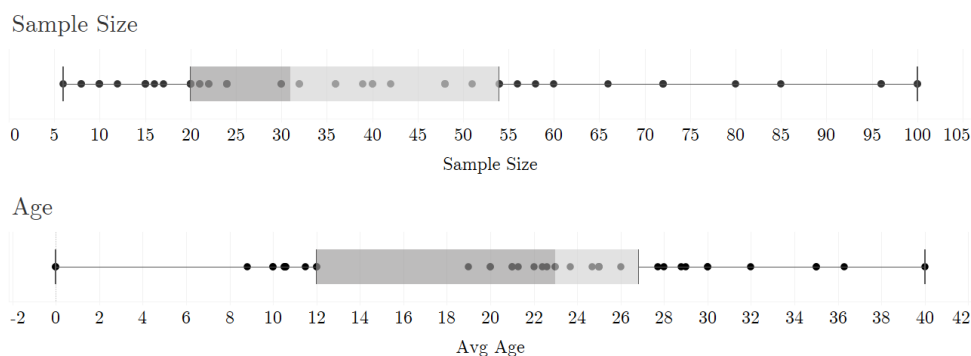


Figure 4.1: Sample size and participant’s age distribution within our corpus of 49 studies data from studies illustrates (figure 4.1), large scale and representative samples are rare

(median sample size: 30 participants, among which the majority presents convenience samples).

4.2 Method

Despite the absence of a common vision of CSCL, researchers usually provide implicit insights on their underlying vision of collaboration in their work. Consequently, we can map the studies' results to the three collaborative process dimensions of the PAC Framework: Participation, Awareness and Coordination. We searched each paper for terminology that aligned with the PAC dimensions. As a result, we were able to summarize our findings in a table listing all studies, tool functionalities and their impact by dimension (see table 4.1). Particular attention was paid to studies that did not feature functionalities present in other studies to see if authors noticed the lack of features for collaboration in their setup.

After analyzing the different studies, we **summed up occurrences of each functionality across studies** ($O_{Participation}$, $O_{Awareness}$, $O_{Coordination}$) and their correlation to the PAC space (studies reporting positive effects on either of these three dimensions). The results were then used to construct a **PAC vector**. For example, a functionality that was present in one study positively impacting awareness and coordination and, in another study, impacting awareness and participation, would result in a vector of (1,2,1) in the PAC space. In order to account for studies specifically studying a single functionality, we corrected these vectors by the number of functionalities in these studies.

$$PAC_f = \left[\frac{O_{Participation}}{Avg(N_{f,Participation})}, \frac{O_{Awareness}}{Avg(N_{f,Awareness})}, \frac{O_{Coordination}}{Avg(N_{f,Coordination})} \right]$$

where $N, O \in \mathbb{N}, PAC_f \in \mathbb{R}$ (4.1)

Hence, a functionality that was the only one present in the tool of each study would generate a weight of 1 (the number of copresent functionalities) whereas functionalities that shared a tool with other functionalities would result in weights smaller than 1 (reducing the impact of the dimension on the vector direction). To this end, for each study, the **number of copresent functionalities** (N_f) was counted and reported for the identified PAC dimension ($N_{f,Participation}$, $N_{f,Awareness}$, $N_{f,Coordination}$). Then, for each functionality, the respective **average** (Avg) of these numbers was calculated, so that a functionality correlating with two or three dimensions and being tested individually on one dimen-

sion (arguably a very interesting scenario) would then have more influence on the vector direction, then, for example a functionality that co-existed with others. For example, a functionality impacting participation in 3 studies and awareness in 2, but being tested on awareness individually and participation with two others, would result in a vector of $(3/3, 2/1, 0) = (1, 2, 0)$.

Equation 4.1 depicts the underlying formula: Each component of a functionality (f) vector consists of three values in the PAC space. Each number of occurrences N in a dimension is weighted by the mean of occurrences O of the functionality among other functionalities within a study tool by dimension. Finally, we used the calculated vectors to represent each functionality in a diagram relating collaborative processes and tool functionalities (figure 4.4). We further analyzed the different metrics per functionality category and identified common combinations of functionalities within tools.

4.3 Results

Ideally, a functionality is tested in isolation on a number of independent studies to confirm the findings. Yet, functionalities did not occur in isolation, which shows that Sugimoto *et al.* (2004) is a representative case of tool design as stated in the introduction of this dissertation part. Overall, tools consisted, on average, of three functionalities, in a range from 1 to 6 (see figure 4.2).

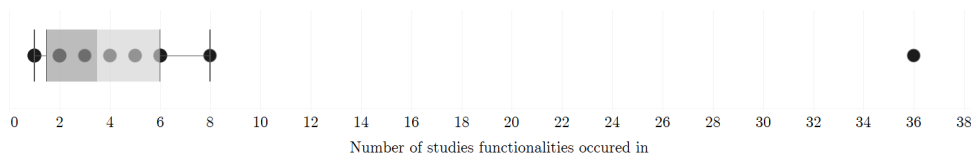


Figure 4.2: The number of times functionality occurred in different studies

No significant difference (Mann-Whitney U test) could be observed between functionality categories (figure 4.3). Functionalities that were studied more exclusively were participation feedback and process building (see figure 4.3 - left). Every functionality occurred on average in five studies. Due to the high presence of parallel input, the mean of five is significantly higher than the median of three studies.

The analysis shows that parallel input appeared 36 times across the 49 studies of the corpus. Functionalities impacting only one dimension of collaborative processes are rare – the more functionalities included in studies, the more dimensions are impacted. This is

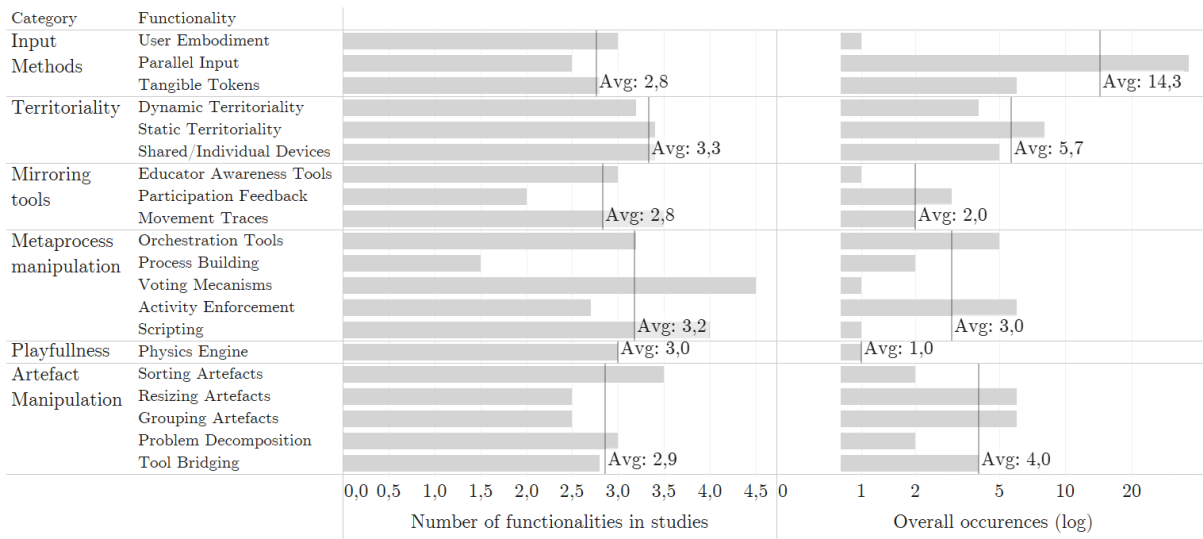


Figure 4.3: Number of copresent functionalities in studies (left), number of studies in which the functionality occurred (right)

due to both potentially more functionalities in different tools and the complex interplay between functionalities. The functionality that has been studied the most exclusively (1,5 functionalities per tool) was tool bridging.

In addition, functionalities were most often associated to the Participation dimension first (on average 3.5 times/functionality) before Awareness (with 2.9 times/functionality) and Coordination with 2.5 times/functionality. Table 4.1 provides a distilled view of the data. Reported are the Occurrence by functionality over all studies, the average number of co-present functionalities in the same study, the PAC-vector and the total number of studies the functionality occurred in. Figure 4.4 visualizes the results. Since many functionalities improve more than one dimension, we opted for a Venn-diagram with three overlapping green areas representing the three PAC process dimensions. Collaborative conditions (gray) influence collaborative processes in these dimensions and vice versa. In fact, figure 4.4 is another, albeit partial view on the PAC Framework. The position of each functionality is calculated by the formula in equation 4.1 and mapped onto the space in figure 4.4. The three dimensions can be considered “attraction points” to each functionality so that a functionality with a vector $[1, 0, 0]$ (e.g., “Physic engines”) will be attracted by Participation only. Functionalities that have been found to impact all three collaboration dimensions are present in the middle of the diagram. The legend is composed of the functionality name, the number of occurrences in our study (n) and a short description. This vision provides multiple insights: Firstly, there seems to be a
















N°	Tool Functionality	Occurences in corpus			Number of copresent functionalities in studies			PAC Vector			N
		$O_{Participation}$	$O_{Awareness}$	$O_{Coordination}$	$Avg_{Participation}$	$Avg_{Awareness}$	$Avg_{Coordination}$	$V_{Participation}$	$V_{Awareness}$	$V_{Coordination}$	
1	 User Embodiment	0	1	1	0	3	3	0	0.3	0.3	1
2	 Parallel Input	19	17	11	2.5	2.5	2.5	7.5	6.7	4.3	36
3	 Tangible Tokens	3	4	2	2.7	2.3	3.5	1.1	1.8	0.6	6
4	 Dynamic Territoriality	3	2	0	4	3	0	0.8	0.7	0	4
5	 Static Territoriality	5	4	3	3.2	3.8	3.3	1.6	1.1	0.9	8
6	 Shared/Individual devices	5	4	3	3	3.5	0	1	1.1	0	5
7	 Educator Awareness Tools	0	1	0	0	3	0	0	0.3	0	1
8	 Participation Feedback	3	1	0	0	1	0	4.5	3	0	1
9	 Movement Traces	1	2	0	3	3.5	0	0.3	0.6	0	2
10	 Orchestration Tools	1	2	2	4	3	3	0.3	0.7	0.7	5
11	 Process Building	1	0	2	3	3.5	0	0.3	0.6	0	2
12	 Voting Mechanisms	0	1	1	0	3	3	0	0.3	0.3	1
13	 Activity Enforcement	4	2	1	3	2.5	2	1.3	0.8	0.5	6
14	 Scripting	0	1	0	0	2	0	0	0.5	0	1
15	 Physics engine	0	1	1	0	3	3	0	0.3	0.3	1
16	 Sorting Artefacts	1	1	1	3	4	3	0.3	0.3	0.3	2
17	 Resizing Artefacts	2	2	3	2.5	3.5	2.7	1.5	1.1	0	6
18	 Grouping Artefacts	4	3	0	2.5	3.5	2.7	0.8	0.6	1.1	6
19	 Problem Decomposition	0	2	1	0	3	3	0	0.7	0.3	2
20	 Tool Bridging	2	0	2	3	0	2.5	0.7	0	0.8	4

Table 4.1: Occurences, average number of functionalities and PAC vectors

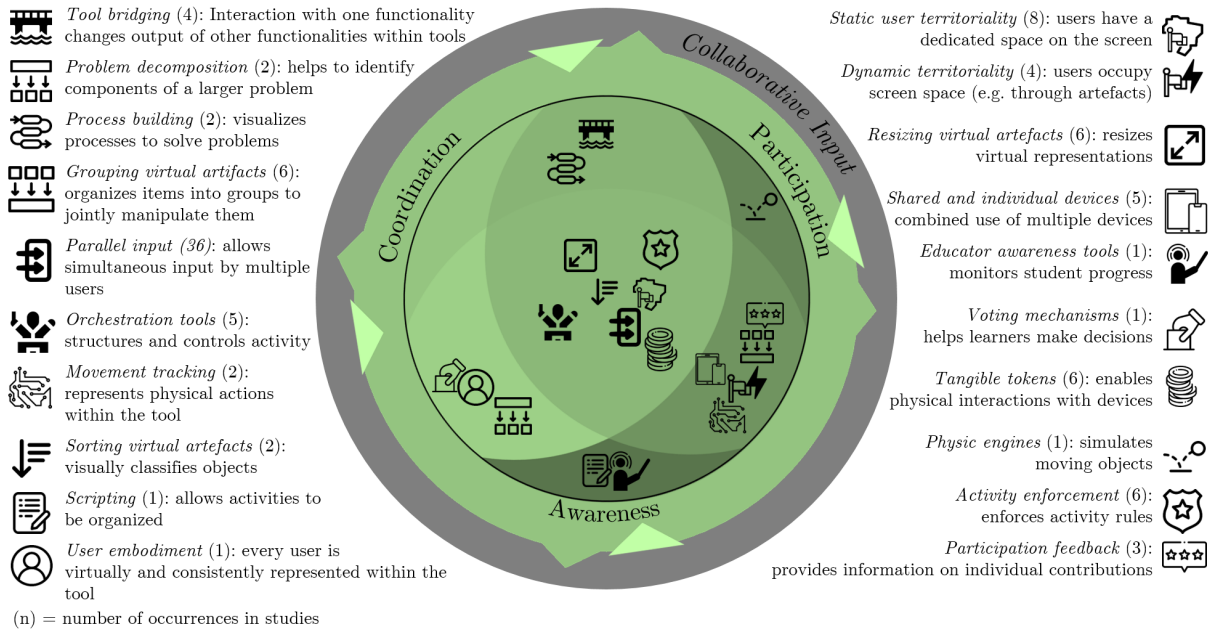


Figure 4.4: A visualisation of the PAC Mapping of collaborative functionalities to the collaborative process dimensions.

general tendency towards Awareness and Participation. Indeed, there is no functionality exclusively linked to Coordination. The Awareness-Coordination cluster accounts for three functionalities while Participation-Awareness contains five. Functionalities with influence on all three PAC dimensions are distributed among an area closer to Participation and Awareness then Coordination flow.

4.3.1 Functionality Categories

Since we grouped similar functionalities in categories, we investigated whether the category affiliation was reflected in its impact on the process categories. The majority of established categories of functionalities in the previous chapter (Artifact manipulation, Input Methods, Mirroring Tools, Metaprocess Manipulation, Territoriality and Playfulness) does not appear as clusters in the visualization (figure 4.5). This may either mean that the categorization has potential for improvement, or that the underlying data does not allow a precise mapping on the three dimensions. Two categories seem exempt from this observation: The category of territoriality seems to exist on an axis between participation and awareness; mirroring tools seem predominantly support processes of awareness and to some extent, participation. The latter confirms the observation of study authors

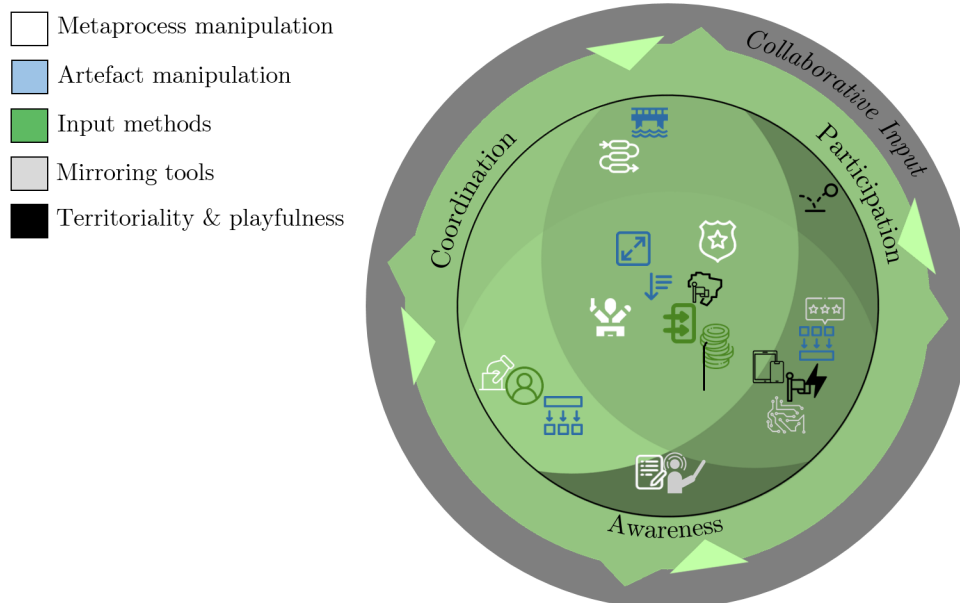


Figure 4.5: PAC Mapping: functionalities colored by category.

who observed that awareness on participation may regulate over-performers but may not increase participation from under-performers (Yvonne Rogers *et al.* 2009).

4.3.2 Combinations

As stated at the beginning of this chapter, functionalities do not exist in isolation. We thus identified the five most common couples and triples of functionalities. Due to the omnipresence of parallel input in most setups, all combinations contained parallel input as a component (figure 4.6). Its presence among any functionality does not change the position of the latter within the visualization (compared to figure 4.4). In turn, the position of triplet components changed considerably for some functionalities, such as orchestration tools, resizing virtual artefacts and dynamic user space attribution (highlighted in figure 4.7). Others stayed in place, such as tool bridging, or movement traces (not highlighted in color). The change in position has been highlighted in figure 4.7 through arrows, starting from their isolated position in figure 4.4. The change in position is due to a less frequent occurrence of triplets compared to individual functionality. For instance, parallel input is a very frequent functionality, which, on its own, is present in many studies but in combination with two others (e.g. resizing virtual artefacts and orchestration tools) only occurs twice. These two studies would otherwise have a lesser impact on the position

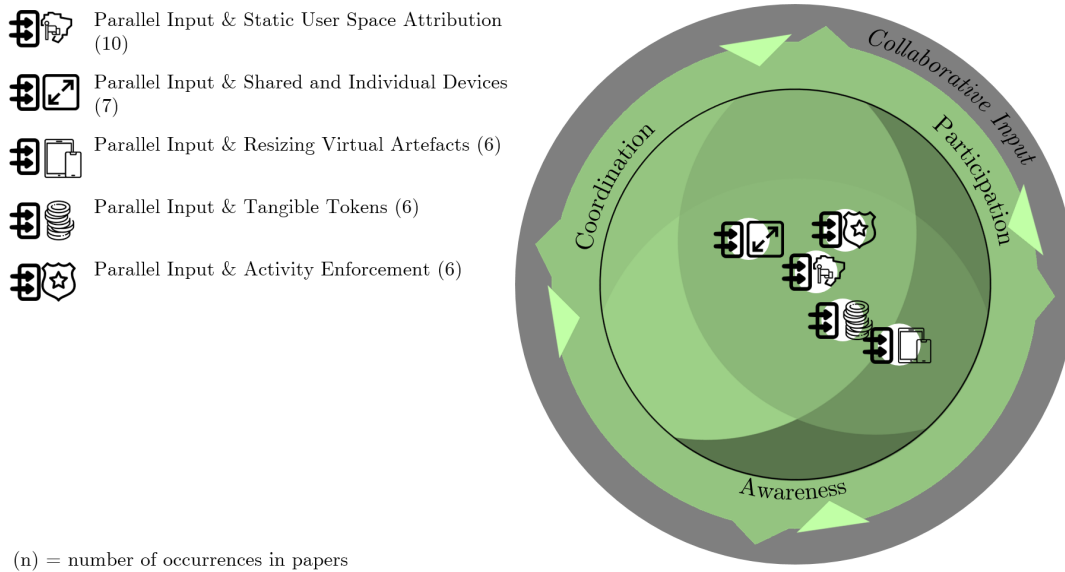


Figure 4.6: Functionality couples in the PAC space

of parallel input. If this behavior can be confirmed with more studies, one could infer a dominant functionality within software for a certain collaborative process dimension. Given the low number of occurrences (2), this might simply be due to the fact, that considering less studies means a higher likelihood of complementing each other in only one or two dimensions. We further noticed, that the two studies for the identified triples with movement tracing functionality and resizing artefact functionality have been conducted by the same authors at different moments in time, another source of bias.

4.3.3 Conceptual Framework Contribution

The results of this chapter can be considered a contribution to the PAC Framework of part I, just as the list of functionalities in the previous chapter details the framework’s “tool” part. Links have been established between individual processes and process dimensions. However, the number of total links does not allow for a visual integration and, shows, once again, the limits of a visualization of all collaborative processes and tool functionalities. Nevertheless, we can consider the contribution of this chapter a (preliminary) design framework, since it can be used to target specific collaborative processes (figure 4.8).

Instead of attempting an overall visualization through interconnections between all collaborative functionalities and the PAC dimensions, the following example illustrates the documentation of study results (confirmed links) of a participation feedback func-

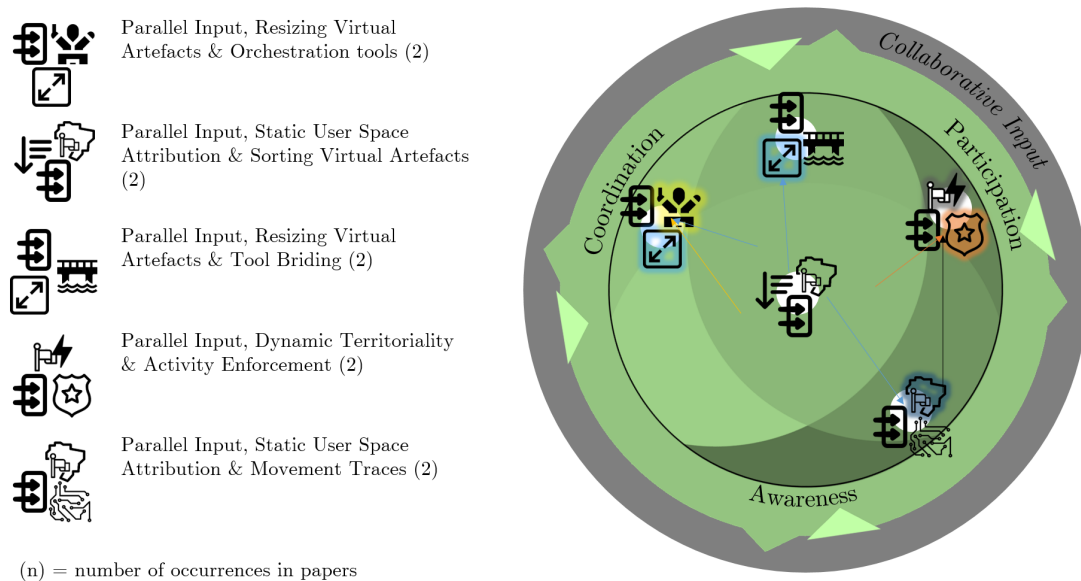


Figure 4.7: Functionality triples (arrows depict position of component functionality compared to their position in figure 6)

tionality in figure 4.9: Bachour *et al.* (2010) conducted a study on collaboration during a problem solving activity where the participants, in a group of four, had to solve a murder mystery task around a tabletop displaying discourse time per member or topic. Each participant was handed a folder with logs of the murder case investigation, like maps, news articles and interviews. Each folder was different and complementary, thus ensuring positive interdependence during the experiment. The group had to choose one of three suspects. Bachour *et al.* (*ibid.*)’s target of the study (Rummel 2018) was the awareness ① of participants on the resource “talking time”. Albeit not specified, the awareness type fits behavioral awareness. The hypothesized objective ② in turn was an equilibrium of participation.

Although this functionality (implemented as a Wizard of Oz), was used exclusively in the context of the activity of a murder mystery puzzle, it is not functionally tied to it. The functionality can potentially be used in other collaborative contexts. The missing arrow between activity and tool (figure 4.9) reflects this fact. We thus not only hypothesize a priority among functionalities to support certain collaborative processes, but additionally distinguish between activity dependent and activity independent collaborative functionalities. For instance, displaying discourse participation visualization is a functionality that we hypothesize can be appropriate independently of the designed activity. In turn, functionalities like sorting and grouping artefacts only makes sense with activities where users

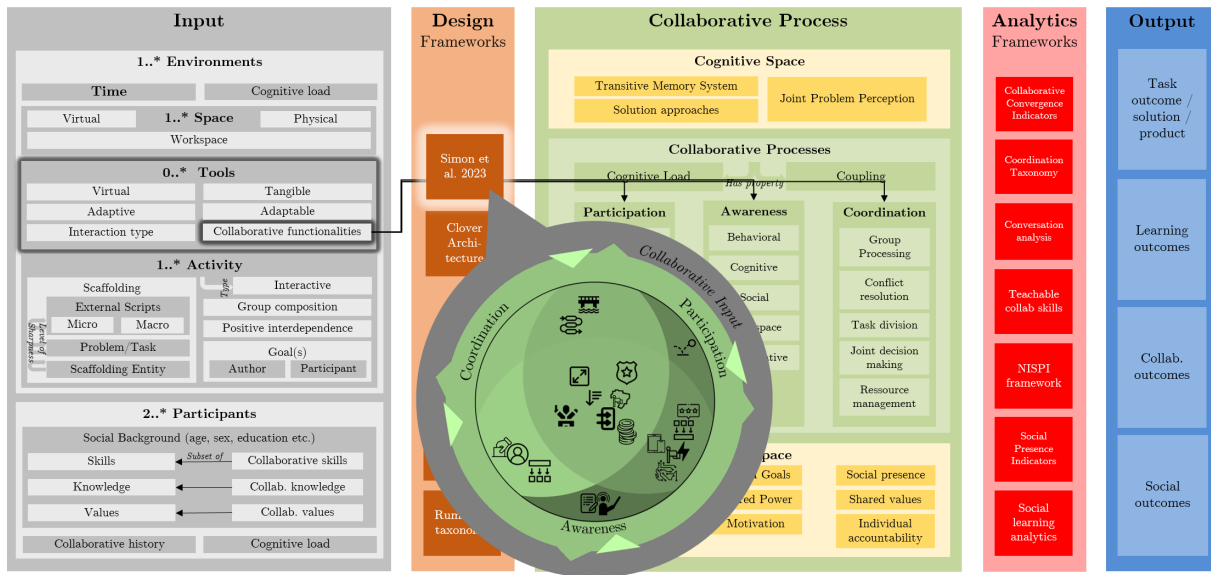


Figure 4.8: The mapping of this chapter as a design framework within the PAC Framework

have to handle multiple artefacts, such as brainstorming tasks.

4.4 Limits

The first and foremost limitation to this work is its **missing link to the underlying activities**. Indeed, functionalities, especially in the context of research on collaborative processes and collaborative learning, are oftentimes implemented in conjunction with the activity. This may not be true for all functionalities however, since some functionalities support general collaborative processes that naturally occur in any collaborative setting, such as awareness and decision making, the latter of which profits from tools such as voting mechanisms. Voting mechanisms, for instance, can illustrate that the current work still can be detailed further on the functionality side: Should voting mechanisms include a history of decisions taken to support group processing? Does the functionality support different electoral systems (Arrow *et al.* 2002)? The level of detail on the collaborative process side is also unsatisfactory to some degree, given the level of detail that the current framework provides. Ideally, links could be established between processes and functionalities directly. It is however important to note, that due to the lack of a common conceptual framework in the community, the overall corpus of selected studies could not provide further information on which processes have been supported by the identified functionalities (for instance, it could be deduced that the “awareness” type investigated by Bachour *et al.* (2010)

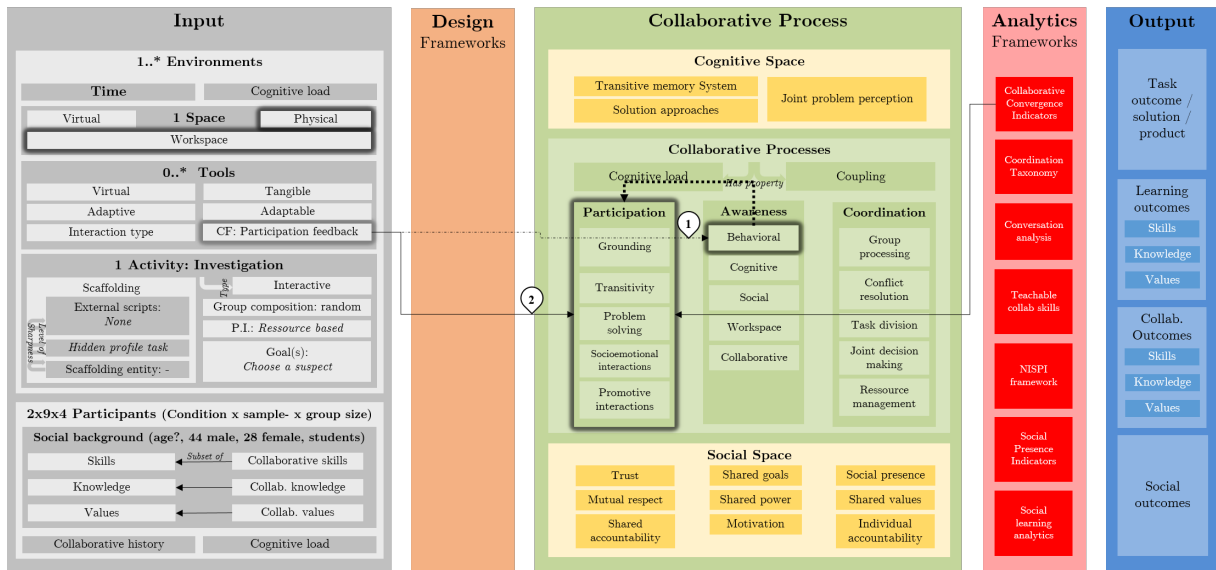


Figure 4.9: The conceptual framework applied to Bachour et al. (2010). Design Frameworks hidden for better readability

was behavioral awareness, but the paper does not further distinguish the type of oral participation for example). Finally, the nature of links between process and functionality is, at best, of indicative nature due to the variability of settings and activities, participants' backgrounds etc. In order to reveal the true nature of the impact of tools to collaborative processes.

4.5 Conclusion on the PAC Mapping

In this chapter, we have **investigated the impact of tool functionalities on collaborative process dimensions**. Through the analysis of **49 studies**, we have identified the possible support for collaboration of **20 functionalities** (and subsequently, combinations thereof) on collaboration. This (as far as we are aware of) first of its kind effort, is an effort dedicated to the design of better groupware (and CSCL systems in particular), which we hope can be extended in the near future to overcome the outlined limitations.

SUMMARY ON COLLABORATIVE SOFTWARE

In this part, we **investigated and illustrated how functionalities impact different aspects of collaboration**, based on a **literature analysis of 49 studies**. As a result, we identified **20 tool functionalities** in the first chapter of this part and detailed their potential impact on collaboration in the second chapter. The resulting **mapping** is a first, although evolutive, step towards a better understanding of the interplay of tools and collaboration. We wish to underline the importance of the collaborative research effort that is required to expand on this work. Both at the functionality level, conceptual level and the nature of linking, we see potential for collaborative work. Albeit the level of sharpness seems sufficient for the current body of research, further defining the scope of functionalities, conceptual processes and the way tools can influence the latter seems like a necessary precondition for increasing comparability and reproducibility of future studies. We estimate that only with conceptual clarity, of which a common conceptual ontology is a prerequisite (requiring a collaborative community effort), and common experimental standards for activity design and methodology, which have yet to be established (Martinez-Maldonado *et al.* 2021), our initial results can be further consolidated and collaboration itself improved and better understood. Meanwhile, the visualizations of chapter 4 provide a first tool for the **choice of functionalities** and indicate what aspects of collaboration are likely to be impacted by a given tool.

PART III

Collaborative Hardware

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CONTEXT

In the previous part of this dissertation, we have identified and mapped 20 functionalities to three categories of collaborative processes (PAC functionality mapping). While these functionalities have software-side implementations, they also require hardware affordances (as does every interaction). Hardware may enable, favor or prohibit the use of software functionalities. We refer to “hardware” as the physical component of computer support defined in part I. It also shapes how users interact with software functionalities.

Entry Points

Kirsh (2001) instigated the concept of “Entry points”: “structures or cues that represent an invitation to enter an information space or task”, which was later refined into a design principle (making those entry points accessible, “points of prospect” and “progressive lure” Yvonne Rogers *et al.* (2009)). In the context of hardware for collaboration, entry points can be visual devices (cameras, screens, lights etc.), tangible devices (actors, touchpads, buttons or tokens) or acoustic affordances (microphones, speakers). We further distinguish input entry points (the user has the opportunity to input information) and output entry points (the user can access information). For meaningful human-computer interaction to occur, an information system offers typically at least one input and output entry point.

Interactive Tabletops - Collaborative Hardware

In the previous 15 years, **tabletop systems** (see figure 4.10) have been the preferred device for **co-located collaborative learning environments**. Interactive tabletops consist of a large horizontal screen and a device to capture multi-touch input. In the early 2000s, researchers built these devices with projectors and machine vision. With the availability of large, integrated touchscreens since 2005, small study research could be conducted with reduced investment into customized hardware, increasing the number of conducted studies on collocated collaboration.

In terms of entry points, these devices typically can handle at least 16 concurrent in-



Figure 4.10: An interactive tabletop for mediated colocated collaboration (Barthès et al. 2012)

teractions on the surface and some can be used in conjunction with tangible tokens (as for example demonstrated by Jetter *et al.* (2011)). Another aspect of the provided number of entry points is their flexibility in terms of space: Users can interact on the whole surface, which supports dynamic territoriality (a concept introduced by S. D. Scott *et al.* (2004)). Furthermore, tabletops facilitate turn-taking, a resource access-management strategy deployed whenever the number of entry points is inferior to the number of group members. Turn-taking occurs predominantly during conversations, since talking time has to be split up, but depending on tool affordances, tools may also constitute a resource on which group members have to organize turn-taking. While an essential part of collaboration, organizing turn-taking draws cognitive load. The functionality **parallel input** helps to limit such strategies to conversational turns.

As mentioned in the introduction of this dissertation, there are **drawbacks to this device**: mainly its **cost** (even if the device can now be purchased, a 40" tabletop starts at 1500 € as of June 2024), its **bulkiness** (inappropriate for mobile settings) and **power consumption** (requires a power outlet). Moreover, the large screen **attracts attention** from group members constantly, even when it is not required. It has been suggested that this might reduce efficiency of other collaborative processes, such as behavioral awareness (Zagermann *et al.* 2016). Driven by the advantages (as well as the disadvantages) of the

interactive tabletop, we investigate, in this part of this dissertation, **the possibility of creating a mobile alternative.**

Structure

To do so, we firstly investigate existing mobile technologies for collaboration with a shared workspace. In chapter 6 we then inquire suitable human-computer interaction types for collaborative settings through four identified criteria based on our conceptual understanding of collaboration. Having identified a promising interaction type, we present criteria for a possible technology to implement the previously identified interaction type and design choices in chapter 7. These technological criteria guide a selection process in a technological state of art in chapter 8. The result of chapter 8 is a set of promising technologies for the implementation of the identified interaction type, which, in chapter 9 lead to the design and implementation of six prototype variants in 18 different versions. Finally, we

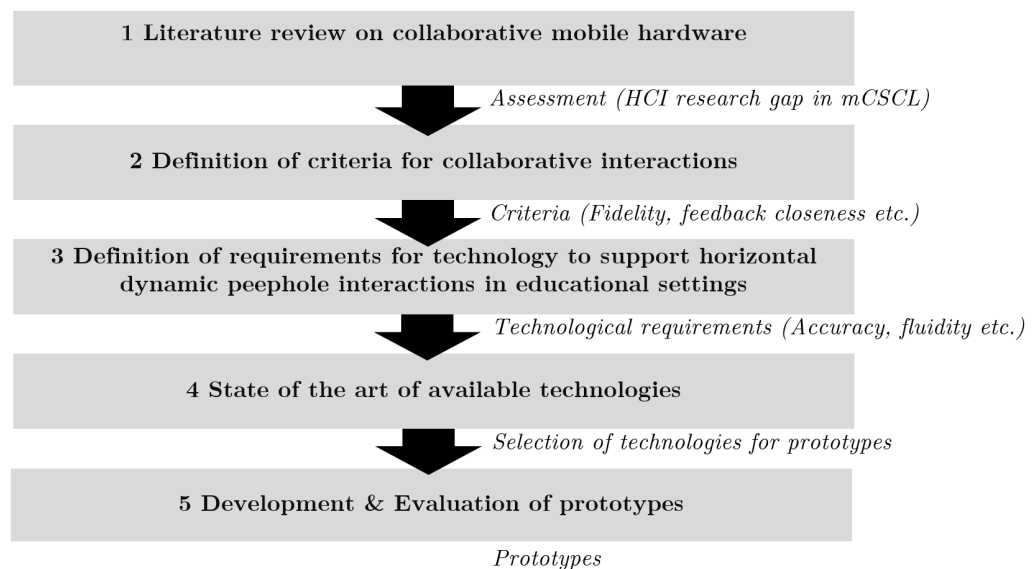


Figure 4.11: The structure of the hardware part

conclude with an overall evaluation of the developed prototypes. Figure 4.11 illustrates this structure.

Related Publications

Simon, S., Marfisi-Schottman, I., and George, S. (2024, September). An In-depth Analysis of Localization Technologies for Affordable Augmented Reality on Surfaces. *Trends and Foundations in Human Computer Interaction*. Under submission.

Simon, S., Marfisi-Schottman, I., and George, S. (03/2024). SPART – An Affordable Mobile Augmented Reality Alternative to Interactive Tabletops in Education. In *Proceedings on E-Society 2024 and Mobile Learning 2024*, ML 2024, In press. Porto, Portugal. Best paper Award.

MOBILE COLLABORATIVE LEARNING SUPPORT

Dedicated hardware design for collocated CSCL settings has its origins in the early 1990s with the emergence of both CSCL and CSCW (Stahl, 2006). The development is tightly coupled to a shift in the field of Human Computer Interactions (HCI) with new technologies to address collaborative practices through groupware systems.

5.1 Collaborative Hardware

Since the first attempts to support collocated collaboration through dedicated infrastructure, such as the Colab project at Xerox from 1987 to 1992 (Stefik *et al.* 1987), the variety of available hardware solutions to interact with virtual artefacts in collaborative settings has steadily increased. Tong (2017) provides an extensive review of existing Multi-Surface-Environments (MSE) which have been part of HCI research since the 1990s and are the predominant configuration in industry (meetings, cowork sessions etc.). The authors conclude that, whatever the chosen configuration of mixed or single screen setups, one screen acts as shared collaborative space in which users can “perform the collaborative process, such as sharing information, exchanging ideas, discussing and negotiating”. When multiple devices are introduced, they are always considered private spaces.

The authors argue that, in terms of orientation of a shared screen (vertical or horizontal), there are both advantages and disadvantages. Horizontal screens allow for more users to easily gather around the shared space, but content orientation is a challenge (text can be difficult to read from the opposite site of the screen). On the other hand, vertical setups cannot welcome as many users (if interaction is to happen directly on the screen) but do not have the content orientation issue. Works by Y. Rogers and Lindley (2004), as well as Potvin *et al.* (2012) also show important affordances for collaboration through horizontal screens such as more cohesive group work, more discussion, and better balance in participation and discussion support.

Large tabletops have been extensively used in research projects but remain

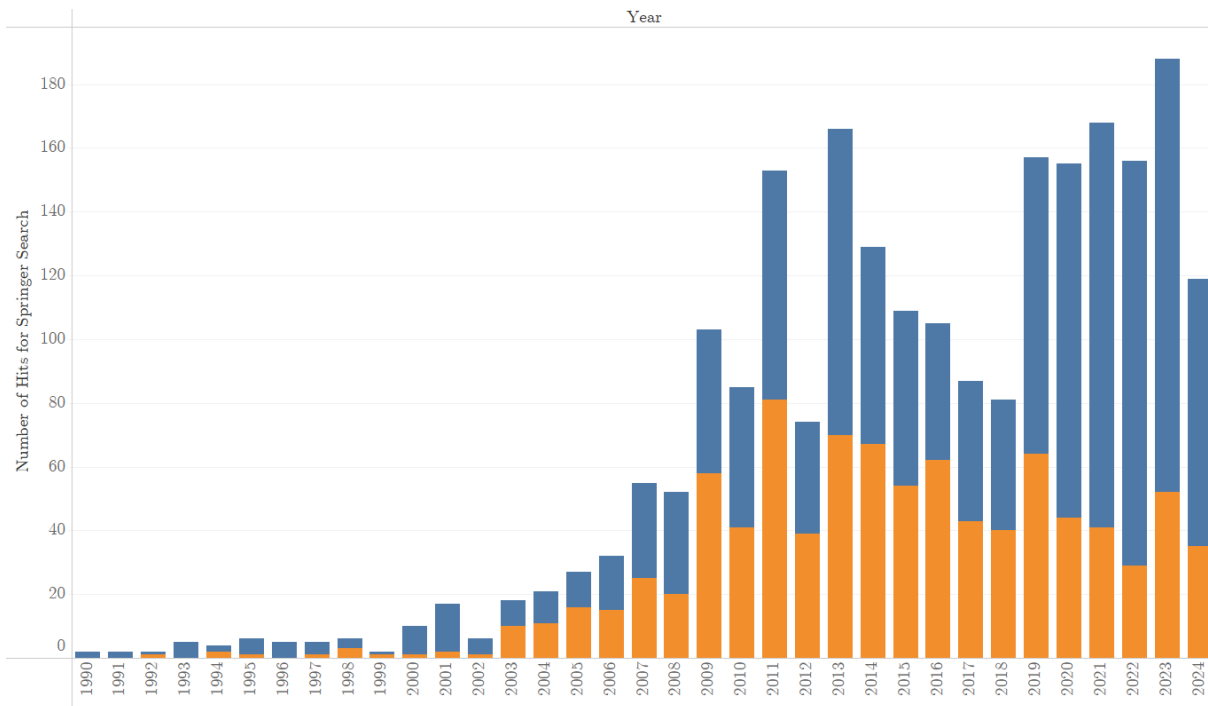


Figure 5.1: Springer database hits for "interactive tabletop" (blue and orange stacked) and "interactive tabletop collaboration" (orange) by year

rare in classrooms, due to their high cost and immobility. Indeed, even though, after 20 years in existence, tabletops (considering 40" touch screens or larger) are commercially available, their high cost (currently 1500 € and above) and restrained software support (user interfaces) make them niche products. The lack of dedicated applications is of no issue to research, where software is typically designed for isolated experiments (Evans *et al.* (2016), Martinez-Maldonado *et al.* (2013)). Furthermore, due to their horizontal setup, tabletops require dedicated room arrangements reducing flexibility for other activities in the same room. These limitations seem to explain why interactive tabletops, albeit enjoying growing popularity in the context of collaboration and beyond (see figure 5.1), have not yet been integrated in classrooms or other settings where collocated collaborative computer support is of interest.

5.2 Existing mCSCL Support

Mobile CSCL (mCSCL) focuses on the use of more affordable and mobile devices, such as smartphones and tablets, for collaborative situated learning settings such as field trips.

However, mobile devices lack the screen space that a tabletop offers. Especially manipulating virtual artefacts collectively or in parallel becomes more difficult.

Augmented reality (AR) can be used to transform available space into interactive working areas. Yet, classic camera-based AR technology requires the mobile device to be held at a certain distance from the augmented surface. This results in two issues: Extended use can lead to muscle fatigue (Pereira et al., 2013) and holding the device with both hands can make it challenging to interact with virtual or physical objects at the same time, especially for children. Additionally, using AR in a group setting raises its own set of challenges. If a person holds a single device, others in the group have to gather around this person to view the augmented content (which seems to apply for any content viewed on a single device in a mobile setting (Serna *et al.* 2016)). Alternatively, if all group members use their own device, this reduces awareness of what other group members or the teacher are doing, which is crucial for collaboration.

AR goggles, such as Microsoft’s HoloLens, could address these issues but remain expensive hardware for educational contexts (4000€ per item) and introduce other problems such as motion sickness (Kaufeld *et al.* 2022). Those devices also rely on additional controllers, voice or gestures for interaction. Virtual reality devices, such as headsets, face complementary challenges of representation of the other, since movement tracking as of this writing does not translate all the user’s body movements into virtual space. Precisely of this, virtual reality headsets might be of interest to study which behavioral information is essential for collaboration. Nonetheless, these devices, for now, present the same disadvantage as their tabletop counterpart: a high price tag hindering adoption in classroom settings. Current goggles (06/2024) also are either heavy on the head of the user or require external batteries. Indeed, albeit their theoretical application outdoors, augmented or virtual reality headsets face the fundamental problem of weight (battery) and motion sickness, making them uncomfortable to wear over longer periods of time.

Hybrid configurations of one or multiple mobile devices to form a common workspace have been implemented. For instance, Nielsen *et al.* (2014) presented *Juxtapinch*, a collocated photo-sharing groupware solution to display large photographs on multiple aligned devices (figure 5.2). Rädle *et al.* (2014) developed a similar device called “Huddlelamp” with the ability to locate mobile devices on a table and support them as entry points in a common virtual workspace. Although advised as low cost and portable, it still requires a support for a camera to track the devices and a separate device to run the software. Furthermore, the work does not present any user study to evaluate the quality of interactions

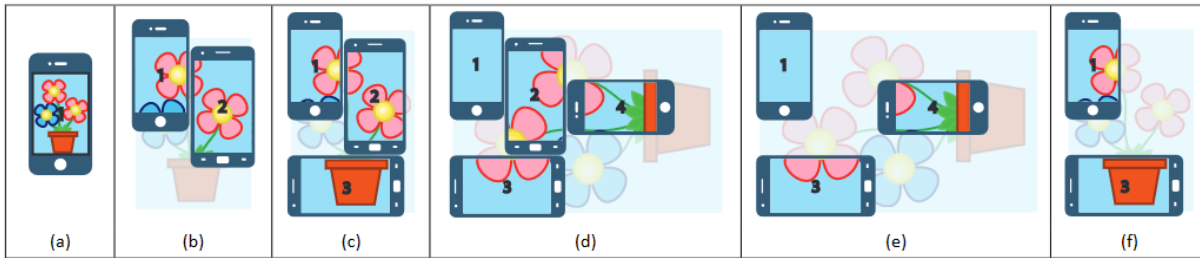


Figure 5.2: Juxtapinch mobile device configurations, Nielsen et al. 2014

for collaboration, nor do any derivative works.

Even though these last configurations have not yet been tested, they seem particularly promising because of their potential to recreate similar conditions offered by a large interactive tabletop to support collaboration. It seems reasonable to argue that using one or multiple smartphones might come as an advantage compared to tabletops. Indeed, research on screen sizes suggests that smaller screens have the potential to benefit collaboration, as large tabletops tend to attract user’s attention to the screen at the demise of social awareness of other team members - even when attention to the screen is not required. Smaller screens seem to distract users less and lead to a more goal oriented usage (Zagermann *et al.* 2016). The study has, however, been conducted on an information retrieval task, where the advantage of multiple entry points seems less salient.

5.3 Conclusion on Existing mCSCL Support

In this chapter we presented studies that illustrate the different affordances of mobile devices for a shared space for collaboration. Studies have outlined the potential and drawbacks of AR techniques both integrated in devices like tablets and AR goggles, as well as the possibility to use multiple devices like tablets to form a larger screenspace in mobile settings. The question that remains is: **what kind of interactions can be enacted with the presented technologies (mobile devices), and whether these interaction types are susceptible to enhance collaboration.** To address this question, the next chapter will define criteria for interactions suited to support collaboration around small screens and present an interaction type that, according to these criteria and the affordances of large tabletops, seems promising.

INTERACTION TYPES FOR VISUAL REPRESENTATIONS

6.1 Introduction

In the previous chapter, we have explored different ways to support collaboration and collaborative learning through tools. We have identified interactive tabletops as effective tools for collaboration and collaborative learning due to their large workspace and horizontal orientation. At the same time, we have identified its shortcomings for mobile settings and group member awareness. Other solutions for collaboration in mobile settings have been identified, even if their effectiveness is yet to be proven. Nevertheless, it seems that a shared screen, even of smaller size, is of interest for collaborative tasks. However, there are many ways to engage with a central, even smaller device. In this chapter, we will investigate which type of interaction is the most promising for this scenario. In the realm of Human-Computer Interactions (HCI), designing interfaces that are intuitive and efficient is paramount. The effectiveness of an interface is often determined by how well it aligns with the user's cognitive and physical abilities and habits. To effectively support collaboration, the interaction to navigate virtual content has to be natural in order to draw low cognitive load, required for collaboration or learning processes (as explained in part I). To this end, we first propose four criteria (Fidelity, Accuracy, Feedback closeness and Realism) that will be used to evaluate possible interaction types and conclude on the most suitable interaction type for mCSCL.

6.2 Criteria for Evaluating MCSCL Interactions

Fidelity refers to how closely physical movements map to virtual movements within an interface. High fidelity interactions offer a direct and proportional relationship between the user's actions and the system's response. This variable is crucial for ensuring intuitive control and minimizing the learning curve associated with new interfaces. The principle is also known as spatial compliance (Jr *et al.* 2017) and reduces the “gulf of execution” a

concept brought forward by Norman (2013). The gulf of execution describes what a user can do with a system. If the system offers affordances the user can refer to from experience, the gulf is narrowed and the user does not have to spend a lot of time discovering and training the usage of those affordances. Headtracking in virtual reality (VR) headsets like the Oculus Rift or the HTC Vive offers high fidelity by mapping real-world movements directly to the virtual environment. Users can navigate and interact with the virtual space similarly to the physical world, leading to an immersive and intuitive experience without the need to actively translate a movement in physical space to a smaller or bigger movement in virtual space. In contrast, for example the use of keyboard arrow keys for the navigation of a webpage can be considered low fidelity: The discrete, non-continuous input requires users to translate their intended movements into a series of key presses, increasing cognitive load.

Accuracy refers to the exactness of an interaction. Having to correct for errors or inaccuracies within a device, leads to the user having to repeat or execute complementary interactions leading, in turn, to complementary cognitive load (Sears and Shneiderman 1991). An indicator for accuracy is Fitt's law which has been successfully applied to HCI (MacKenzie *et al.* 2001). Graphics tablets are examples of devices which offer high precision for tasks like digital drawing and design. The stylus provides fine control over input, allowing for detailed and accurate manipulation of virtual objects without any correction. In contrast, trackpads or computer mice often lack the accuracy for meticulous tasks. The indirect nature of the input can lead to inaccuracies and necessitates frequent corrections.

Feedback closeness measures the immediacy and directness of visual or tactile feedback of the interface. Close feedback helps users quickly understand the effects of their actions, thereby reducing cognitive load and improving task efficiency. Examples of high feedback closeness are touchscreens or haptic feedback systems, such as VR gloves, which enhance usability giving feedback at the spatial position and time of user action. Drawing tablets without integrated screens can be considered an instance of low spatial feedback closeness, since the user draws on the tablet but the feedback appears on a separate screen. This can make it challenging for users to maintain precision without extensive practice. Temporal closeness refers to the time between the user action and the feedback the system provides. Ideally, feedback is immediate and proportional (intensity).

Interaction realism refers to how naturally the interaction methods mimic real-world behaviors. High interaction realism leverages users' innate skills and experiences, making

the interface more intuitive and reducing the cognitive load required to learn and use the system. For example, systems like Microsoft Kinect use body movements for control (e.g. jumping may make an avatar jump on the screen), which align closely with real-world actions, offering a high degree of interaction realism. In comparison, using for example electroencephalography headbands to control a robot's position has novelty character and no real-world counterpart (since users are supposed to focus in a certain way to generate voltages on the sensors), and thus is an interaction type that has to be acquired by the user.

6.3 Assessing Visual Interaction Types

The interplay between the four criteria presented above (degree of fidelity, precision, feedback closeness, and interaction realism) impacts the cognitive load associated with using an interactive device. An ideal interaction aims to maximize these variables to create a seamless, intuitive, and efficient user experience.

In the context of displaying and interacting with visual content beyond screen dimensions, different interaction types have emerged. Command-Line Interfaces and symbolic navigation allow to navigate nested logical structures like graphs (e.g. hierarchy based folder structures) by linking interactions like clicking on an icon to the appearance of information associated to the symbolic representation. In terms of Interaction realism, the introduction of the GUI paradigm was a positive development: Albeit still requiring the use of indirect input devices (such as computer mice), clicking on icons to launch programs, execute commands or access files, the interactions mirrored more closely real world behavior as compared to the use of textual commands. The latter also have to be memorized, reducing accessibility (Feizi and Wong 2012). The introduction of peephole interactions further increased accessibility and interaction realism. "Peephole" refers to the fact that the display represents a smaller window into a larger virtual space (in the case of the peephole, the room behind it). Through gestures, the virtual content is moved behind the peephole in what are considered **static peephole interactions**. Static peephole interactions are widespread: On smartphones, one-dimensional peephole interactions allow the navigation of list-like structures, like social media feeds. Map navigation involve 2D peephole interactions combined with zoom gestures. The navigation of 3D video games or virtual 3D environments via mouse and keyboard can be considered static 3D peephole interactions.

Dynamic peephole interactions distinguish themselves from static peephole interactions essentially by making the device a controller to navigate virtual content. Instead of using gestures on a screen or other means, dynamic peephole interactions enable users to access content by moving and pointing the device itself to the physical position to which virtual content is associated - the device effectively becomes a mobile window into a virtual overlay to the physical environment. If the movement of the controller matches the movement on the screen, virtual content can be associated to a position in the real world. This is the case for instance in virtual or augmented reality interactions.

Dynamic peephole interactions thus seem promising in terms of **fidelity** and **interaction realism**. 2D peephole interactions seem appropriate to implement a large horizontal working space with small screens. Although 3D peephole interactions can be enacted with mobile devices such as tablets and smartphones, the only technology currently available in off the shelf hardware is camera based. This means that the device has to be hold constantly to display virtual elements on its display, a restriction problematic for a workspace that should be visible to all collaborators. Ideally, the device displays augmentations when placed and moved across a surface. The use of spatial memory (since virtual elements can now be located in physical space) facilitates remembering the position of virtual elements beyond the screen (Munoz-Montoya *et al.* 2019). To further reduce such cognitive efforts, the underlying, static surface can consist of visual cues (e.g. a map), visible at all times. (figure 6.1). The resulting interaction features high **feedback closeness**, since the user action of sliding the device results in a feedback timely at its current position. For the remaining part of this dissertation, we call this horizontal dynamic peephole interaction **SPART** (on-Surface Positioning Augmented RealiTy).

For collaboration, such a central device would allow users to peripherally keep track of their group member's actions, an important affordance of horizontal touchscreens while attracting less unnecessary attention (as do larger screens in tabletops). Additionally, the static support can provide (even if less interactive) entry points through annotation or coloring. The complementary advantage to the natural exploration of virtual content is the illusion of associating virtual information to physical space. This particular interaction has been found to be highly effective for participants of studies to retain information (*ibid.*). Given the benefits of the SPART interaction, in the section, we will inspect existing contributions implementing SPART.



Figure 6.1: Illustration of SPART: A horizontal dynamic peephole interaction on a static support

6.4 Existing Work on Dynamic Peephole Interactions

Among the most cited papers for dynamic peephole interactions with mobile devices in collaboration is Sanneblad and Holmquist (2006), for a device to facilitate routing activities with a tablet in front of a projected, vertical map. The authors note that absolute positioning, as required for the peephole interaction, is not trivial to implement. In their setup, a stationary Mimio XI system (commercial ultrasound and infrared location setup for digital whiteboards, 700€ as of May 2024) was connected to a laptop to localize the mobile device. In a preliminary user study, this setup was compared to a static peephole interaction as used in current map navigation (zoom and drag). Users' efficiency on the **vertical** dynamic peephole setup was significantly lower compared to the traditional map application. The experiment was dominated by the observed ergonomic deficits as users simultaneously had to hold a tablet and interact with it. When given the choice between the prototype and the typical zoom and pan map application (static peephole interaction), users picked the latter, mentioning the fear of breaking the device and ease of use as reasons for their preference. A more similar study to the horizontal peephole setting proposed in SPART, was carried out by Rohs *et al.* (2007). They tested map navigation

using a phone’s camera tracking either its position relative to a map or just with spatial awareness (without a printed map underneath). Both of these dynamic peephole interactions performed significantly better than the static peephole interaction enacted by a mobile phone with joystick navigation (Nokia N80) in a usability study with 18 participants who had to find the cheapest parking spot on a virtual map. The setup however still required users to hold the phone at a minimal distance to the static support, instead of it physically lying on the support. Moreover, the dynamic peephole interactions suffered from technological setbacks (robustness of positioning) which underlines the technological challenges in providing a reliable dynamic peephole interaction (Rohs *et al.* 2007). Similarly, a study with projector phones suggests that, even for first-time users, these can be just as effective as traditional tablet map apps for navigation tasks. Research by Kaufmann and Ahlström (2013) showed that participants using a projector phone with a dynamic map segment controlled by rotating the phone performed just as well as those using a traditional pan-and-zoom tablet application without extensive training. Similarly, M. Miyazaki and Komuro (2021) observed positive results with minimal training for a classic augmented reality (AR) map search task, indicating that even this relatively new technology can be effective - indicating fidelity, accuracy and feedback closeness.

6.5 Conclusion on MCSCL Interactions

In this chapter, we identified four criteria for interaction design and explored the potential of existing interactions, which led us to identify a promising interaction called SPART. SPART is a **horizontal peephole interaction** to augment a static support (e.g. a map) by sliding a smartphone or a tablet on its surface. Theoretically, SPART combines both, a low estimated cognitive load (originating in fidelity, feedback closeness and interaction realism) for its user, and a large workspace without the disadvantages of current AR and VR headsets. The design of an implementation of this interaction will be described in the following chapter, and its successful implementation in a mechanical variant thereafter.

OPEN SCIENCE AND REQUIREMENTS

7.1 Introduction

In the previous chapter, we have identified SPART, an interaction type using mobile devices on static surfaces, to obtain a tabletop-inspired interaction. Given the innovative character of the interaction, in this chapter, we will describe and argue the chosen design method and establish a set of criteria with which the prototypes have been evaluated.

7.2 Problem

Research prototypes typically come with novelty design and expensive components. In order to become accessible to other scholars or a larger community, these prototypes typically need to be redesigned to reduce costs and commercialized by a company. An example is the interactive tabletop hardware discussed in previous chapters, which in the early 2000s has been implemented through the use of projectors, machine vision, infrared technologies and other approaches. These individual and costly prototypes (custom design and components) were developed for individual studies, before the availability of large commercial interactive touchscreens. However, this commercialization process takes time and strategic marketing actions from private companies. Yet, in the context of novel HCI prototypes, extensive testing in different contexts is necessary to confirm initial findings and broaden understanding of how these prototypes can help support task or learning related processes. It is therefore important to make sure other researchers can recreate the SPART prototype to conduct studies and explore its use in other contexts to confirm our initial results (presented in part IV).

7.3 Open Science

Open Science constitutes a paradigm that

"scientific knowledge—including data, observational and experimental design and methods, analytical and modeling code, as well as results and interpretations of these (e.g., as reported in publications)—can and should be made freely accessible to anyone, and represented in transparent and reusable formats as early as practical in the discovery process, by employing standards-based technology tools. Frequently encompasses all of open access, open data and open source and, minimally, facilitates reproducibility of results."

(Hampton *et al.* 2015). Behind this paradigm stands the idea that sharing the many details of research processes during studies leads to more rigorous and accountable research that can be more easily continued by other researchers and is open to contributions from non-researchers. Furthermore, beyond open data, open source and open access of papers, it seems especially important, in the context of HCI, to make the production of a research prototype as accessible as possible. Thus, we integrated criteria of accessibility in our specifications for the prototype, in terms of low material cost, available hardware but also the possibility to produce a functional prototype without advanced skills in electronics and computer science. The reasoning behind this is three-fold:

1. Encourage other researchers to build and conduct experiments with SPART to contribute to our initial studies' insights on SPART's role in different contexts.
2. Allow teachers to produce them in class for use in educational settings.
3. Include the community of hobbyists and enthusiasts in further, community-based development of hard- and software for SPART.

7.4 Requirements

The SPART peephole interaction described in the previous chapter requires the device's (smartphone's or tablet's) ability to accurately determine its position, relative to the surface it is placed on. In the following paragraphs we present the requirements a prototype has to comply with to not only implement the interaction ①, but also to function in outdoor situated learning settings ② through a design that favors replication and adoption ③. We identified the following requirements and numerated them to trace their origin:

1. **Accuracy** ①: The technology allows to retrieve the device's position with an accuracy of one centimeter or better. This assures that the user can easily associate

the virtual content on the screen of the mobile device with its underlying surface and that the virtual content is close to the real position of its static counterpart (spatial feedback closeness).

2. **Fluidity** ①: When the device is slid on the surface, the technology allows for as little delay as possible when updating the image. The requirement to achieve a good reactivity is therefore estimated at a minimum of 10 position updates per second (temporal feedback closeness).
3. **Minimum operating range** ③: A standard size for printed media in Europe is the A3 format, corresponding to a surface of 29,7 x 42 cm. The technology should therefore cover at least these dimensions.
4. **Mobility** ②: Situated learning often uses learning contexts that mirror the educational content, such as field trips (e.g. for biology). The technology should therefore be portable: lighter than 500 g and not exceed dimensions of a notebook (A4).
5. **Robustness** ②: The technology should function independently of outside conditions, such as sunlight, wind or ambient noise.
6. **Affordability** ②, ③: Potential use in educative setups depends on the possibility to deploy the technology in sufficient numbers. Thus, the device price should not exceed 50 € per unit.
7. **DIY and reparability** ②, ③: Ideally, the technology should not require high skills in any specialized area and the production and assembly of a prototype should be within the reach of educators or students. Components should therefore be easily available; assembly should not require tools beyond a basic makerspace, nor should it necessitate a lot of time.
8. **Multi-device support** ①, ③: Prototypes or products should be able to locate multiple devices for multi-device scenarios (at least two). Research on the number of devices in collaborative settings requires at least one central device, but personal located devices seem an interesting research perspective.

7.5 Conclusion

In this chapter, we have established a list of requirements for a SPART prototype for potential use by the scientific community and beyond. In the next chapter, we will describe the technological state of the art that we conducted to determine the best technologies to implement SPART and finally, the prototypes that were developed.

TECHNOLOGY STATE OF THE ART

8.1 Introduction

In the previous chapter we established requirements for a SPART prototype, both rooted in the interaction itself (chapter 6) and the methodology ensuring availability and reproducibility of experiments (chapter 7). In this chapter, our objective is to **identify the best technology to implement the SPART interaction** and, more specifically, an affordable and portable system capable of localizing a smartphone on an A3 piece of paper. We will therefore present a **state of the art of positioning systems, of-the-shelf products** and **the prototypes developed during this PhD**. To this end, we first provide the method and a scoring scheme to estimate feasibility of each design before an extensive list of the identified technologies and their respective scores. Finally, we will argue for the design chosen and present its features in the next chapter.

8.2 Method

Over the course of human history, numerous methods and products for localizing objects have emerged. To ensure our review is comprehensive, we have adopted a systematic approach that combines **localization techniques** with **physical phenomena** (e.g. physical forces). By doing so, we can filter combinations that can be exploited by **technology** to identify of-the-shelf **products**. Finding corresponding products was done with a keyword research in the google search engine in August 2023, specifying physical phenomenon and localization technique. The first 100 results were taken into consideration. If this keyword research did not provide relevant products even though the technology seemed promising in theory, we developed one or more SPART **prototypes** to test its relevance. The complete process is depicted in figure 8.1. Each of the three steps resulted in a set of, either combinations of techniques and physical phenomena, technologies or products and prototypes. We evaluated phenomena and techniques separately (figure 8.1:1), then evaluated the remaining combinations (figure 8.1:2). Then, each technology (figure 8.1:3), and later in the process, the corresponding products and prototypes (figure 8.1:4),

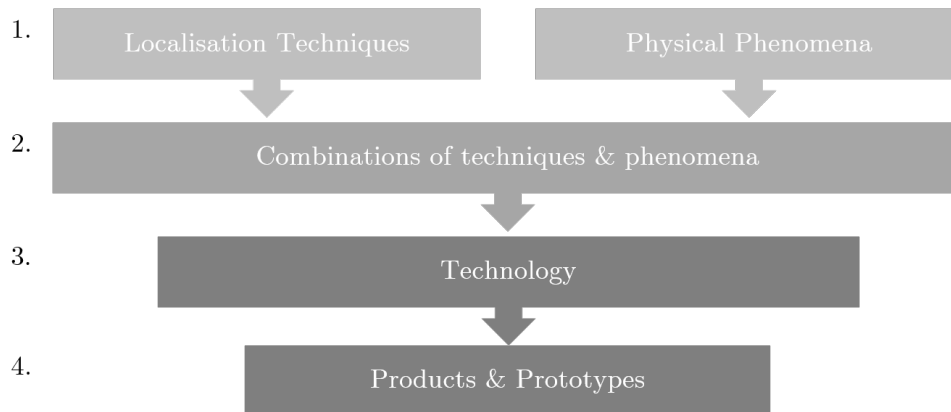


Figure 8.1: Method of the technological state of the art

were evaluated through a **score system** based on the criteria presented in the previous chapter (accuracy, fluidity, minimum operating range, mobility, robustness, affordability, DIY and reparability, multi-device support). The following score scheme was used:

- 0 points if the requirement was not met.
- 0.5 points if the requirement was partially met or if half of all the sub-criteria were met.
- 1 point if the requirement was met.
- 1.5 points if the requirement was met twice (e.g. accuracy better than 0.5cm, multi-device support for 4 devices etc.).

To facilitate the comparison of different technologies, we used the sum of all criteria points. However, failing to meet one requirement completely, resulted in a total score of 0. The highest possible total score is 12. This sequential approach generated a set of promising technologies for our use case, structured in a taxonomy and thus a valuable guide to focus our efforts on for developing a prototype in the absence of a suitable commercial product.

8.3 Technology Review

Initially, we examined the fundamental physical phenomena and available localization techniques for their interest in a positioning system. This approach reduced the number of possible combinations considerably.

8.3.1 Physical Phenomena

As depicted in figure 8.2, only 6 physical phenomena can be used to create SPART. Indeed, among the four fundamental forces, only the **electromagnetic force** and **gravity** are of interest, since devices to even measure nuclear forces would not comply with the criterion of accessibility. The electromagnetic force acts on an atomic level, but through the effect in each atom results in derived forces, (such as the applied force, friction etc.). It is thus important to, on one hand, consider derived and emergent forces and phenomena and the electromagnetic force itself in the form of waves, and, on the other hand, its component forces, which are the **electric** and **magnetic force**. The **applied force** is of interest, since

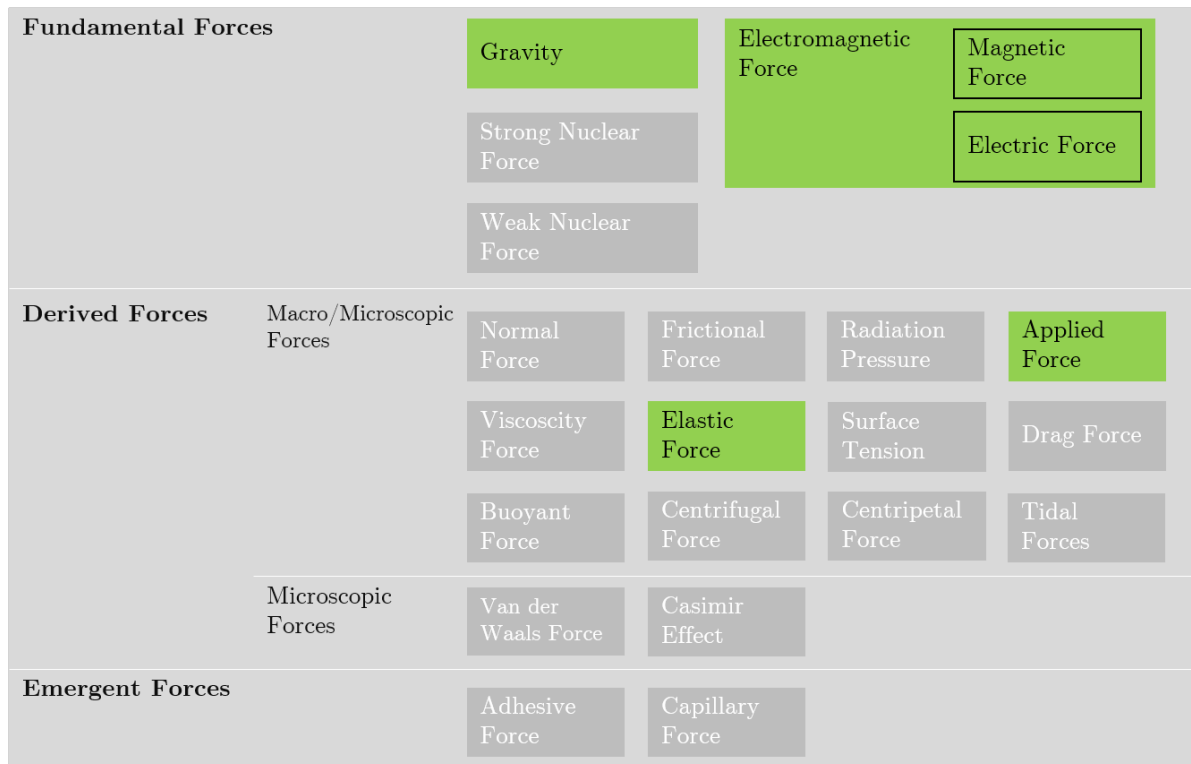


Figure 8.2: A classification of physical forces. In dark gray: Potential use for a positioning system. In red: excluded phenomena

it is the force applied to an object like a smartphone when moved. It can be translated into electrical signals by attached mechanical systems (like a potentiometer for example).

The **elastic force** is used in sensors relying on Hooke's law, stating that the elastic force e.g. in springs is directly proportional to the distance of deformation. If distance can be measured, so can be position through attached sensors. Elastic forces also occur in

pressure waves like sound or vibrations, phenomena with potential for positioning systems due to their (relatively low) propagation speed.

All other forces are not relevant for creating SPART. For instance, the emergent forces are not of interest since the capillary force acts on liquids which cannot be used in our context of gas and solids. Among the derived forces, surface tension and tidal force, as well as the buoyant force and drag force only apply to liquids. Microscopic forces act on a very small scale and thus cannot be used for the positioning systems discussed in this dissertation. Centrifugal and centripetal forces act in a rotational frame of reference which is not the case of the intended context. Frictional forces occur between objects but are directionless and its measurement depends on the applied vertical force, itself depending on the weight of the device and the applied pressure of the user's hand, being variable. In the following sections, we describe how the remaining 6 physical phenomena could be used to create a location system such as SPART.

Gravity

Gravity is the force of attraction one object exerts on another. Since easily measurable forces of attraction occur between objects with different masses, on earth it is the planet's mass that exerts gravitational forces on the objects on its surface, whereas attraction between other objects is negligible. The only directional force vector for use of measurement is thus downwards. The surface on which an object has to be located can be considered a vector field where the pressure varies depending on the position of the object. Consequently, monitoring the surface with an array of pressure sensors is a possibility to provide data for scene analysis techniques. A keyboard is, for example, such a surface monitoring device. Indeed, the position of the fingers of a hand is determined when a threshold force (the switch's spring resistance) is exceeded on the surface covered with mechanical switches.

Electromagnetic Force

Electromagnetism is a composite force originating from the mutual influence between magnetic and electric fields and at the origin of numerous interactions and phenomena of matter in daily life. However, the electromagnetic force itself acts on an atomic level. Its interest for localization stems from the interaction of its component (magnetic and electric) fields which can propagate through matter as waves and interact with the latter. Electromagnetic waves propagate at the speed of light. Their propagation time is

used with trilateration techniques in technology such as radar and lidar. Furthermore, the communication protocols developed on electromagnetic wave transmission with different ranges can be used to provide beacon-based navigation: an object can determine its position when in reach of one or multiple beacons, e.g. radio stations, and on a smaller scale for example through energized NFC tags.

Magnetic Force

The magnetic force is used in magnetic surgery, guiding instruments remotely (Swanepoel *et al.* 2021); positioning systems exceed nanometer accuracy (Massé *et al.* 2016). The Lorentz force is the force that acts on moving, charged particles in a magnetic field. Thus, an object in a magnetic field can use a dedicated circuit with circulating electrons to detect a voltage difference (Hall voltage). As such, the effect can be used for scene analysis in magnetic fields measuring magnetic field vectors. Another force of interest is the electromotive force: A changing magnetic field induces a voltage in a conductor, leading to a current if the conductor is part of a closed circuit. This current can be measured but requires change in the field and thus only can detect moving magnetic fields.

Electricity

Electric fields are generated by electric charges and can exist in the absence of electric currents. The electric forces in an electric field are described by Coulomb's law which states that the magnitude of the electric force between two point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them (Huray 2009). Electric sensors are used in various applications to monitor and measure electric fields, which can provide valuable information about the presence of charged objects, potential differences, and the behavior of electrically charged systems. Capacitance (the capability to store electric charge) is a phenomenon used for accurate distance measurement (use in accelerometers and touchscreens for small distances). It relies on the forces between charged particles and the electric field. An object can measure the surrounding electric field by providing charges (in a capacitor for example). Depending on its distance, the electric field can be measured accordingly. Electric capacitive field tomography has been used for 2D positioning by Zhang *et al.* (2017) to create low cost non-grid capacitive touch pads.

Applied Force

When an object's position changes, it experiences an applied force. This force or impact on its environment can be measured. Industrial robots for instance, use the mechanic rotation of their limbs to accurately maneuver their arms. Actuators like motors put into rotation the robot's limbs. This rotation can be measured with a variety of sensors, and with the known length of the arms, the position of the head can be accurately estimated. The phenomenon of distance and angle variation is thus particularly suitable for the use with geometric techniques. Other derived measures like acceleration (speed changes over time) or speed (position changes over time) can be directly measured with accelerometers and gyroscopes on the object itself. Typical smartphone accelerometers for instance exploit inertial load of reference objects located in the center of a spring array attached to the object.

Elastic Force

The elastic force is behind the phenomenon of elasticity of materials. Pressure waves (e.g. sound waves) can be considered a consequence of compression and depression forces on the molecular level of a system and are thus of interest for determining a position either through pressure waves through materials (vibrations) or surrounding air (sound waves). Since their speed is much slower compared to the propagation of electromagnetic waves (and time differences can thus be more easily measured) sensors and processing speed is less of an issue (compared to electromagnetic wave based systems). The elastic force is behind the phenomenon of elasticity of materials. Pressure waves (e.g. sound waves) can be considered a consequence of compression and depression forces on the molecular level of a system and are thus of interest for determining a position either through pressure waves through materials (vibrations) or surrounding air (sound waves). Since their speed is much slower compared to the propagation of electromagnetic waves (and time differences can thus be more easily measured) sensors and processing speed is less of an issue (compared to electromagnetic wave based systems).

8.3.2 Localization Techniques

Fundamentally, there are three ways of determining the position of an object in space:

- **Dead reckoning** allows a system to locate itself by recording its relative movement since a known position (for example computer mice). In robotics, this technique is

also known as odometry and consists of counting the number of rotations of the wheels of a robot to determine subsequent positions.

- **Geometric techniques** use angles (triangulation) or distances (trilateration) relative (difference of arrival) or absolute (Time of flight) to one or multiple known point(s) to determine the position of a device (GPS etc.).
- **Fingerprinting**, also known as scene analysis requires a mapping of data points of the area wherein the device has to be located. This mapping is created during a phase of preparation (offline phase) during which, for any given point on the surface (or in space), the attributes' values taken into consideration have to be recorded (e.g. signal strength) and associated to the position. During online phase, the device measures the attribute and looks up in its mapping the absolute position recorded. This requires the attribute to be unique for every position.

For the geometric techniques and fingerprinting, either the device, or a second external device in the environment can initiate measurements and calculus. For instance, fingerprinting can consist of the device having measured each point on a surface (active fingerprinting), or, an external device that has a mapping of positions and default values which change through the influence of the presence of the device whose position is to be measured (passive fingerprinting). For example, a keyboard can be considered such an external device which regularly verifies the state of all the switches and when a key is pressed, the change in the global state helps identify the position of the object on it (equivalent to the switch pressed).

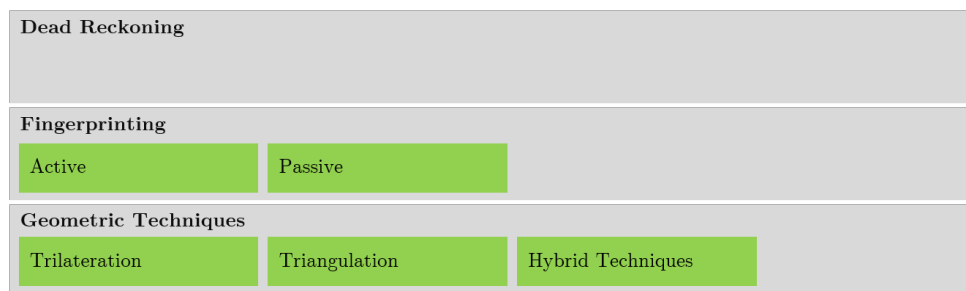


Figure 8.3: Localization techniques summary

There are drawbacks to both passive and active variants. For instance, if the device is to do the measurements, it has to embark appropriate sensors or requires an attached module reducing usability. The use of standard, integrated sensors (such as the magnetometer, accelerometer etc.) of mobile devices would be preferable. Active fingerprinting is agnostic of internal sensors but requires to monitor the entire area. Dead reckoning has an inherent

issue of accumulating errors with every subsequent measurement from its initial, known position due to noise or limited sensor accuracy.

In summary, while there is not one technique to be excluded from the start, dead reckoning techniques all face the issue of relying on previous positions, which means that inaccuracies will inevitably add up to a growing, global error in accuracy over the period of use of the system, requiring the user to recalibrate at certain intervals. Fingerprinting faces the challenge of an attribute that is both different and stable at each position, and, if an offline phase is necessary, this is likely to impact system usability negatively. For active fingerprinting to work, an external device is mandatory and communication with the mobile device has to be established to inform the device of its position. We can conclude that ideally, a device makes use of internal sensors to implement either geometric techniques or fingerprinting techniques, and if dead reckoning is to be used reliably, measures have to be taken to reduce the error between positions to a negligible minimum.

8.3.3 Combinations

Combining the potential **6 physical phenomena** with the **3 localization techniques** presents us with **18 combinations**, illustrated in table 8.1.

As in the previous step, we can further filter these results. To do so, we evaluate each combination for its potential in a positioning system in table 8.1. As can be seen in table 8.1, 14 (out of 18) combinations remain. Combinations have been excluded on the ground of physical impossibility (gravity only acts downwards and is thus incompatible with geometric techniques) or on the ground of environmental influences (electric fields would have to be too powerful to be generated from a battery or might be disturbed by the mobile device's own fields).

8.3.4 Technologies

We identified 37 technologies for the 14 previously identified combinations, as illustrated in figure 8.4. Following the identification of a technology through a keyword research on the google search engine (September 2023), the technology was evaluated against the set of criteria (accuracy, fluidity etc.) from the previous chapter. The results and detailed scores for each criteria are summarized in table 8.2. Every total score different from 0 has the potential to function for our context. With the exception of active, smartphone integrated

	Dead Reckoning	Geometric Techniques	Fingerprinting
Gravity Force	Requires physical bumps on the surface and a 3x3 low resistance mechanical switch array	(Measurable) gravity only acts downwards (on earth)	Measuring where an object is attracted can be measured, e.g. on a keyboard ①
Electro-magnetic Force	Computer mice use EM waves to compare pictures of underlying surfaces to deduct relative movement ②	LIDAR and radar use geometric EM wave techniques ③	EM WiFi field é strength localization exists ④
Electric Force	Environmental interference from electric devices prohibits accurate readings	Electric tomography makes use of electric fields across surfaces ⑤	Touchscreens use changes in E-fields to detect touch ⑥
Magnetic Force	A magnet grid can be read by a hall sensor array ⑦	Rotating static magnets are used for device localization ⑧	Magnetic fields can be mapped and easily measured ⑨
Applied Force	Accelerometers measure applied forces in smartphones ⑩	Redirected applied forces can be measured with geometric techniques ⑪	An applied force can be redirected and measured compared to reference points ⑫
Elastic Force	Standing pressure waves are unreliable due to reflection	Time of flight of soundwaves is used to locate objects ⑬	Sonar is an example of active fingerprinting ⑭

Table 8.1: The combinations of physical phenomena and localization techniques that can be used for a positioning system

sonar, all other solutions require some kind of assembly and DIY skills. Interestingly, a dead reckoning technique is among the top scoring approaches (magnet dead reckoning). However, it has to be seen if the concept can live up to this initial, good score as it only exists as a concept. The active smartphone sonar approach is currently not available for testing.

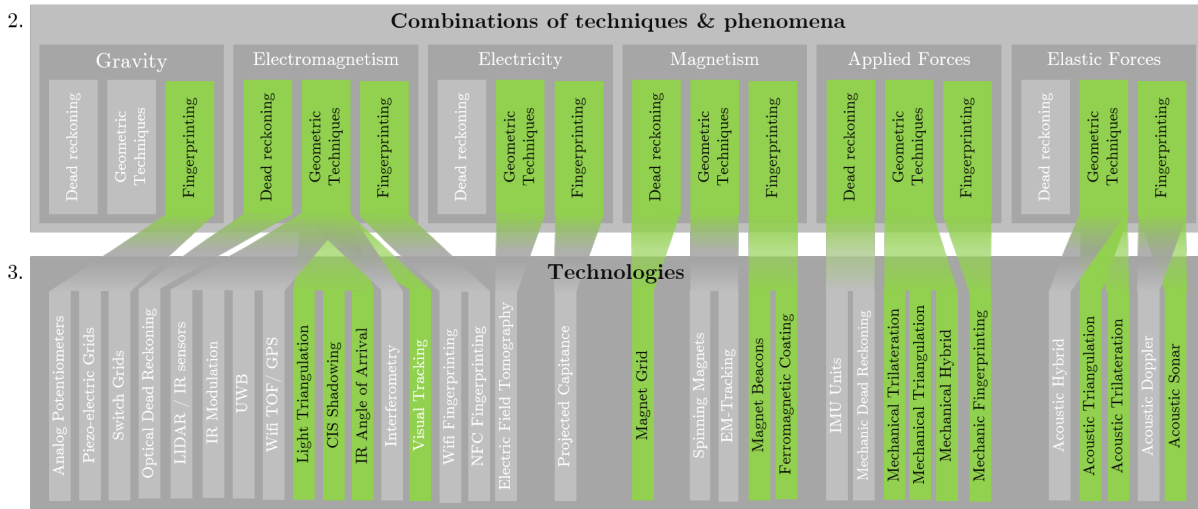


Figure 8.4: Step 2 and 3 of this state of the art resulted in 37 technologies. In gray: phenomena/techniques not fulfilling the requirements

The reason why the number of technologies is much higher than the 14 combinations lies behind the number of different sensors that are available. For instance, electromagnetic waves occur in a variety of spectra and a variety of applications. Table 8.2 summarizes the identified technologies.

As table 8.2 illustrates, there are a number of options that seem promising, most notably magnetic and mechanical approaches. Table 8.2 is ordered by the attributed score. Technologies with a score greater than 0 are a viable option, and will consequently be discussed in the next chapter. The specific evaluation of each of these technologies can be found in Appendix A.

8.4 Conclusion on the Technology Review

In this chapter, we have presented and identified technologies that have the potential to fulfill the requirements for a horizontal, dynamic peephole interaction in line with an extension of open science to the design of hardware. This has been achieved through a

Table 8.2: Summary of evaluated technologies, ordered by total score (0 if one criterion is missed). In bold with an asterisk: prototypes

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multi-device	Total score (max 12)
Magnetic beacons*	1	1	1	1.5	1	1.5	1.5	1.5	10.5
Magnet dead reckoning*	1.5	1.5	1.5	1.5	0.5	1	1	1.5	10
Mechanical hybrid*	1	1.5	1	1	1	1.5	1	1	9
Acoustic trilateration*	1	1	1	1	1	1	1	1.5	8.5
Mechanical trilateration*	1.5	1.5	1	0.5	1	1	1	0.5	8
Mechanical triangulation	1	1.5	1	0.5	1	1.5	1	0.5	8
Light triangulation	1	1.5	1	1	1	1	1	0.5	8
Active sonar	0.5	1	1	1.5	0.5	1.5	1.5	0.5	8
Fiducial marker tracking	1	1.5	1	1	0.5	0.5	1	1	7.5
CIS shadowing	1.5	1.5	0.5	0.5	0.5	1	1	0.5	7
IR angle of arrival	0.5	1.5	1.5	0.5	0.5	1	0.5	1	7
Spinning magnetic markers	0	0	1.5	0.5	0.5	1	1	1.5	0
Analog potentiometers	1	1.5	1	1	1	1.5	1	0	0
Electric field tomography	1.5	1.5	1	1.5	1	0	0.5	1	0
Projected capacitance	1.5	1.5	0	1	0.5	1	0.5	1	0
EM-tracking	1.5	1.5	1	1	1	0	0	1.5	0
IMU dead reckoning	0	1.5	1.5	1	0.5	1.5	1.5	1.5	0
Mechanic dead reckoning	0	1.5	1.5	1.5	0	1.5	1	1	0
Piezo-electric sensor grid	1.5	1.5	1	1	0.5	1	0	1.5	0
Switch grids	1	1.5	1	1	0.5	0	0	1.5	0
Acoustic Doppler effect	0	1	1.5	1	1	1	1	1	0
Acoustic triangulation	1.5	1.5	1.5	1	1	0	0.5	0	0
Phase shift & TOF Hybrid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0	0
Active distance sonar	1	1	1.5	1	0.5	0	0	1	0
WIFI fingerprinting	0	0	1.5	1	0.5	1	1	1.5	0
Bluetooth fingerprinting	0	0	1.5	1	0.5	1	1	1.5	0
EM-Doppler effect	0	1.5	1.5	1	1	0	0	1.5	0
NFC fingerprinting	0	0	1.5	1	1	0	1	1.5	0
WIFI ToF	0	1.5	1.5	1	1	1.5	1.5	1.5	0
GPS	0	0	1.5	1	0.5	1	1	1.5	0
UWB	0	1.5	1.5	1	0.5	1	0	1.5	0
Interferometer multilateration	1.5	0	1.5	1	0	1	0.5	0	0
Mouse-based localization	0	1.5	1.5	1	0	1.5	0.5	1.5	0
IR modulation	1	1.5	1.5	0	0	1	0.5	1	0
Lighthouse tracking	1.5	1.5	1.5	0	0	0	0	0	0
LIDAR	0	1.5	1.5	1	0	0.5	1	1	0
IR distance sensors	0	1.5	1.5	1	0	1	1	1	0

sequential state of the art, combining firstly available localization techniques and known physical phenomena, before filtering unviable combinations. Finally, technologies for the different combinations were identified and evaluated against the criteria defined in the previous chapter, leaving us with 14 technologies for possible prototypes. The process and the remaining technologies are highlighted in figure 8.5 (a summary of figure 8.2, 8.3, 8.4, table 8.1, and an implementation of the procedure outlined in figure 8.1).

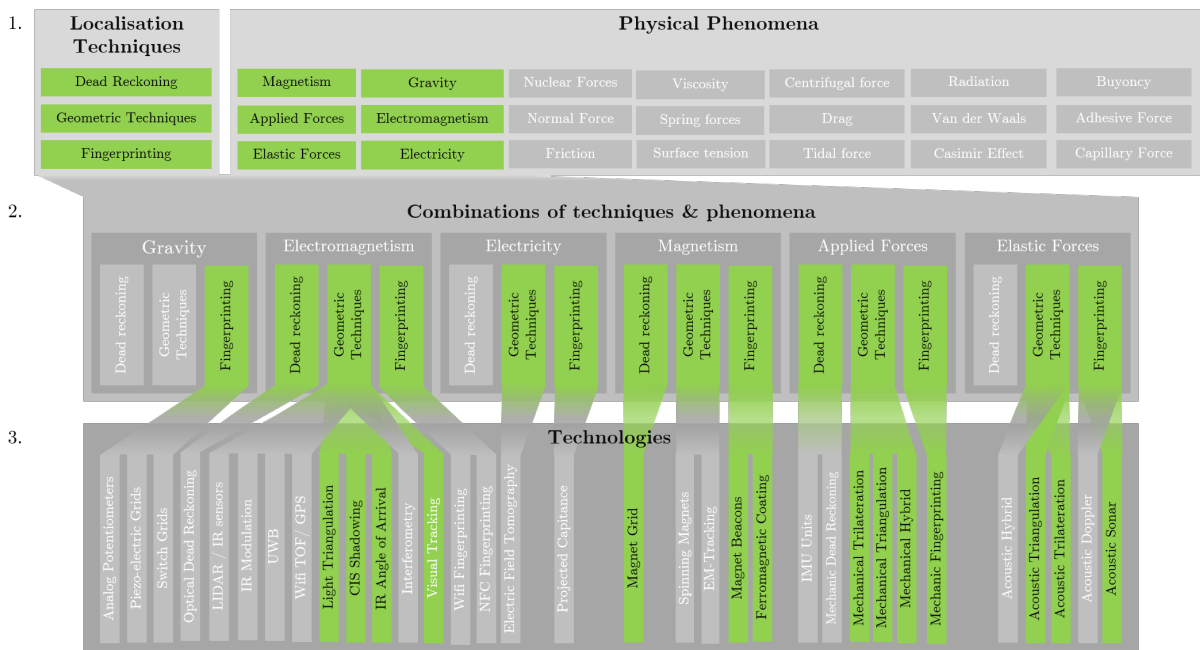


Figure 8.5: A summary of this chapter's results and methodology. In gray: technologies/phenomena/techniques not fulfilling the requirements

The identified technologies include acoustic, magnetic, mechanic and visual approaches. In the next chapter, we will examine the viability of these approaches through a practical implementation and report our results.

PROTOTYPE DEVELOPMENT

9.1 Introduction

The previous chapter has provided us with promising technologies to develop prototypes implementing SPART, based on **magnetism, acoustics, computer vision** and **mechanics**. In this chapter we detail our efforts to implement a functional prototype fulfilling the criteria established in the previous chapter. The prototypes have been developed to study the SPART interaction type in two CSCL field studies described in the following part of this dissertation. We will describe each of the functional prototype's hardware, electronics and software design, before evaluating them against the criteria described in chapter 7.

9.2 SPART-MA: Magnetic Prototypes

Magnetism as a phenomena and current sensor technology comes with interesting properties. Most notably, magnetism is an unperceivable phenomenon and its fields can be created and manipulated with static magnets. High-resolution magnetometers are a standard feature of all current mobile devices and can measure magnetic fields in 3 dimensions. Powerful neodymium magnets are available in different shapes and sizes for a small investment (e.g. 5-10 € for a magnet of 50 mm x 5 mm x 1 mm, France, 06/2024). The technologies surrounding magnetism seemed thus particularly interesting in terms of accessibility, accuracy and a minimum of external devices to function.

9.2.1 SPART-MA Beacon-based prototypes

We conceived a first proof of concept, SPART-MA B V1 I1 (Beacon based, version 1, iteration 1) featuring a single neodymium magnet. Since the beacon technology relies on fingerprinting, during an offline phase, we manually mapped out the magnetic field on a 20x20 cm surface on one side of the magnet with a Fairphone 3 (for which we developed an application that averaged 50 measurements per position in all three dimensions). In

order to account for the earth’s magnetic field’s influence, we initially took a measure (X, Y, Z) of the ambient magnetic field without the magnet and then measured each of the 400 positions on one side of a 5 cm x 1cm x 0,5 cm magnet before associating them to the position of the phone. During the online phase, the phone measures the magnetic field value and looks it up in the mapping created during the offline phase to determine its position on the surface (relative to the magnet’s position). There are a number of drawbacks to this design and procedure:

1. Every online phase begins with an ambient field measurement during which the phone is placed on the surface without the magnet, to account for any rotation of the surface and the magnet since the previous phase (to account for the influence of the earth’s magnetic field)
2. The created mapping depends on the phone’s magnetometer which varies between device models
3. A single magnet’s field can only cover an area of 20x20 cm. Although the magnet’s field is twice this size, every field vector has a “twin” on the opposing side of the magnet, making it impossible to distinguish positions.
4. Strong magnets can disrupt the magnetometer in the mobile device when too close, requiring the user to recalibrate the sensor
5. Ferromagnetic objects (such as nails, screws etc.) can create disturbances in the magnetic field of a magnet, introducing inaccuracies during the online phase

SPART-MA B V1 thus does not fulfill the requirements (see table 9.1)

Table 9.1: Evaluation of the SPART-MA beacon prototype(s)

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-MA B V1 I3	1.5	1.5	0	1.5	0.5	1.5	1.5	1.5	0

To remedy the issue of range, we designed SPART-MA B V2 I1. This version uses multiple magnets to create a magnetic field with different vector values at each position. Since we developed the magnetic field arrangement in a simulation tool (Femm 4.2), we

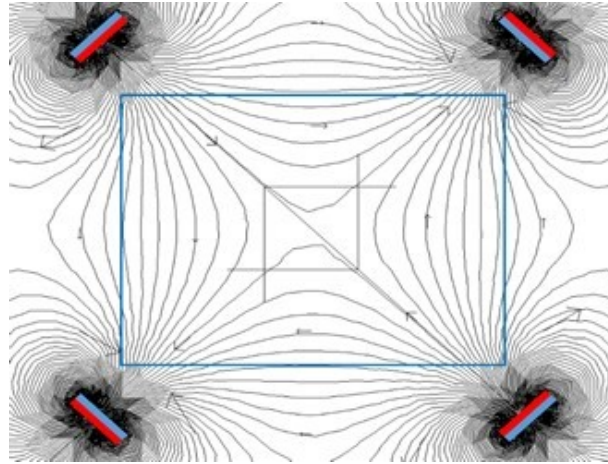


Figure 9.1: Simulation of four static magnets producing a heterogeneous magnetic field around an A3 surface (blue). Created with Femm 4.2

intended to use the data from the model (see figure 9.1) to overcome the manual offline phase and provide a model-based mapping. We hoped that the variation in different magnetometers could be overcome by multiplying the magnetic field values by a scalar value that the user would be able to adjust in a one-time procedure.

The approach worked for the center of the surface (30 x 20 cm) but did not prove reliable towards the limits of the defined area. Using a 3D printer to which we attached a magnetometer module, we mapped out the real magnetic field of the purchased magnets. It appears that conventional magnets neither have the same field strength nor the same field geometry. The real magnetic field therefore did not correspond to the theoretical simulations. Given the impossibility to generalize this approach, it was abandoned. To create geometric magnetic fields, electromagnets are typically used. Replacing the neodymium magnets with electromagnets to create a similarly powerful field is however impracticable due to the high power use and required circuitry.

9.2.2 SPART-MA Coating

Instead of having the magnets around the area of interest, we further investigated the possibility to manufacture a surface inspired by magnetic tape used in audio cassettes or floppy disks in SPART-MA C V1 I1-3. The idea was the creation of a sheet of ferromagnetic material that could be magnetized at different angles at each position for the mobile device to read those orientations with its 3D magnetometer and look up its position based on a table or model (see figure 9.2).

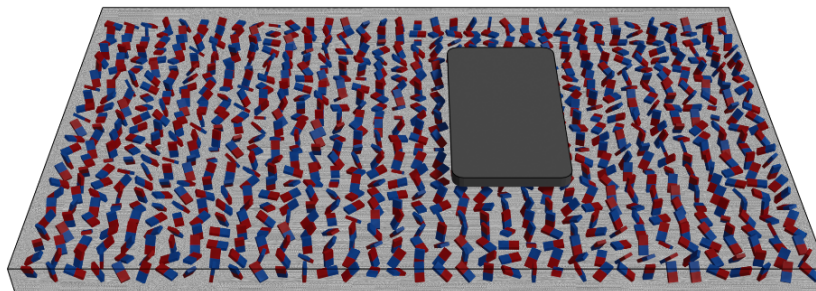


Figure 9.2: Illustration of a magnetic coating prototype: A ferromagnetic material allows to be magnetized at different angles at each position

Initial attempts to magnetize a 2 mm thick surface created from iron powder through strong neodymium magnets at three different angles (90°, 45°) succeeded, but the noise to signal ratio was too high for a more precise distinction. Increasing the layer of the surface would have meant the use of even stronger magnets to magnetize the surface itself and the development of devices dedicated to accurate magnetization (-affordability).

Table 9.2: Evaluation of the ferromagnetic coating version of SPART-MA

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-MA C V1 I3	0	1.5	0	1.5	1	1.5	0.5	1.5	0

9.2.3 SPART-MA Braille

Fingerprinting is not the only technique that can be enacted with magnets. We also developed SPART-MA BR V1 I1-3, a prototype that uses the dead-reckoning technique. To reduce the inherent accumulating error of dead reckoning, we intended to use small neodymium magnets to produce a reference grid the mobile device could detect. In the first iteration, within the range of a magnet, the device could locate itself relative to it and keep a history of these (accurate) readings. When the device would move into another

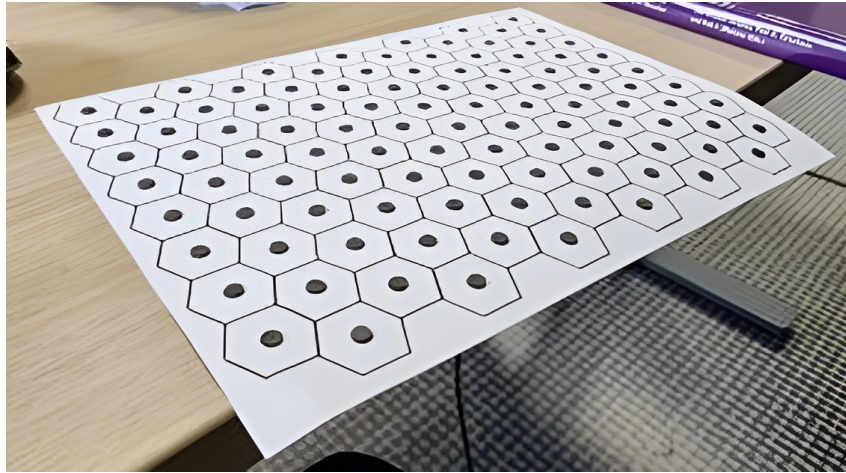


Figure 9.3: An initial prototype with small magnets as magnetic braille

magnet's field, it would rely on this history to determine into which of the neighboring fields it had moved. We designed a hexagonal grid with neodymium magnets at the center (figure 9.3).

The approach proved unreliable due to relative large zones of uncertainty combined with the problem that the phone's own rotation changes when the user moves the device, adding inaccurate readings to the device's position history and, finally, moving the device in small curves makes it even more difficult to determine the correct neighboring field. Another problem were again the differences in geometry and strength of magnetic fields between magnets.

In iteration 2 and 3 of this approach, magnets were attached to the surface in an alternating pattern with the idea being that the smartphone would be able to detect transitions between the magnetic fields and be able to calculate its position based on the different magnets it had been passed since its initial, known position. A reliable implementation would, just as with the other prototypes, rely however on relatively homogeneous magnets (symmetry and strength), which is not the case with commercially available magnets. The three magnetic prototypes developed and tested show that magnet-based beacon approaches may work for small surfaces but cannot be implemented robustly across different devices and in an ergonomic manner. Despite being one of the most promising technologies identified in the previous chapter, the magnetic approach does not meet the requirements for implementation of the SPART interaction.

Table 9.3: Evaluation of the magnetic braille version SPART-MA BR V1 I1

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-MA BR V1 I3	0	1.5	1.5	1.5	0	1	1	1.5	0

9.3 SPART-AC: Acoustic Prototype

In collaboration with LAUM - Le Mans Acoustic Lab, we developed the SPART-AC prototype to explore the potential of an acoustic trilateration approach (figure 9.5).

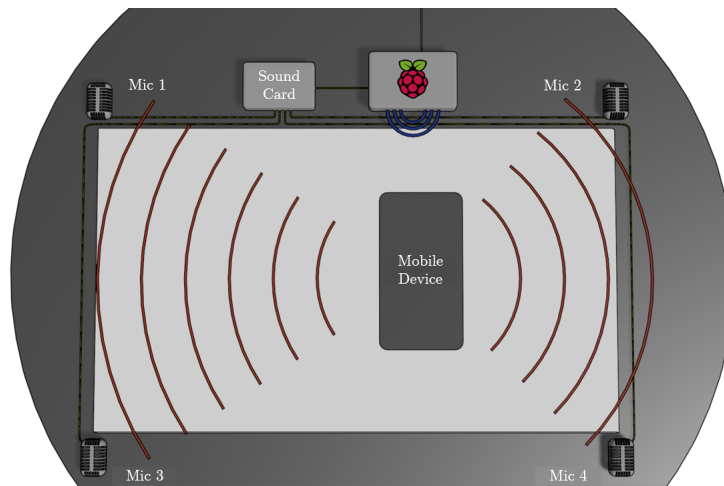


Figure 9.4: SPART-AC illustration: Four microphones capture a sound emitted by the mobile device. Time difference of arrival of sound waves (red) allows for the localization by a raspberry pi computer sending the coordinates to the mobile phone (blue)

The working principle requires an acoustic emitter (such as a smartphone) and is described in 9.4. The emitted sound is then captured by four microphones at the four corners of the A3 surface. The time difference of arrival of the sound can be used to estimate the position of the mobile device by an external device (such as a raspberry pi 3) and can be sent to the mobile device. The current SPART-AC prototype requires a white noise being emitted from the device during 3 seconds. The error in estimation is currently around 2 cm for smartphones; the results are better with an idealized punctual source like a down firing loudspeaker (1 cm). Furthermore, current fluidity (since after each movement, 3 seconds of white noise are required to determine the position) and

Table 9.4: Evaluation of the current SPART-AC prototype

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-AC V1 I2	0	0	1	0	0	0	0	0	0

mobility (the current prototype consists of a round metal plate with a diameter of 90 cm and weighs approximately 5 kg) do not satisfy the requirements.



Figure 9.5: A photo of an acoustic prototype with four microphones and a mobile device as emitter

In summary, while an acoustic localization system is feasible and interesting for its potential of non-audible ultrasound location, similarly to varying properties of magnetometers in mobile devices, speakers in mobile devices vary (in number, position, orientation and design), which makes this approach neither generalizable nor, at its current stage, practical. At the time of writing, the prototypes also are not accurate enough to be used in field studies.

9.4 SPART-ME: Mechanical Prototypes

Mechanical approaches to localize an object in relation to a reference point refer to solutions physically connecting the object to the reference point. Such connections may consist of strings or articulated arms, both attached to sensors that measure the position via angles or distance to the reference point.



Figure 9.6: SPART-ME D (Dual String)- left: potentiometers and strings with microcontroller, right: zoom on augmented content

9.4.1 SPART-ME Two Strings

The first prototype to fulfill the list of requirements presented in chapter 7 is called SPART-ME D V1 I3. It relies on a trilateration method with two strings attached both to the mobile device and two known reference points. The length of the two strings is measured through two string potentiometers, winding and unwinding the strings when the mobile device is moved (see figure 9.6 left).

String potentiometers are industrial components starting at a price of 120 € (France, 05/2023). We therefore developed a partially 3D printed version with Vishay 534B1102JC 10 turn potentiometers (20 €). This prototype uses an ADS1115 Analog to Digital converter to obtain the accuracy required for sub-centimeter localization.

The prototype needs some calibration measurements before it can be used. Firstly, to transform voltage readings of potentiometers into distances, for each potentiometer, two reference measurements V_{init1} and V_{init2} , corresponding to two lengths of unwound string r_{init1} and r_{init2} have to be registered. With this information, given a voltage V , through the equation 9.1, the corresponding length r can be calculated:

$$r = r_{init1} + \frac{r_{init2} - r_{init1}}{V_{init2} - V_{init1}} \cdot (V - V_{init1}) \quad (9.1)$$

With this information, complemented through the distance U between both potentiometers, the position of the attached object can be determined with equation 9.2:

$$P_{x,y} = \left(\frac{r_1^2 - r_2^2 + U^2}{2U}, \sqrt{r_1^2 - x^2} \right) \quad (9.2)$$

Figure 9.7 illustrates equation 9.2. The potentiometers are situated on the x-axis with one at the origin at the other at distance U to the origin. Microcontrollers, such as the

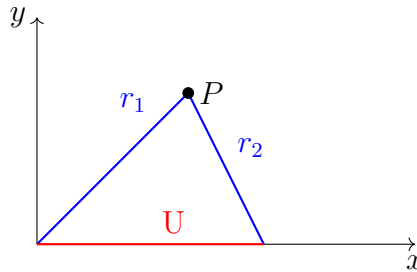


Figure 9.7: Illustration to equation 9.2 to determine the position of P relative to the origin (0,0), given U and r_1 and r_2

ADA3176 Feather M0 used for this first version, execute a main execution loop after a setup code block. The main execution loop first reads the values off the two potentiometers and checks if these values have changed within a defined threshold. If so, the position is calculated and sent to the connected Bluetooth device, where the virtual layer is offset by the position which results in the effect of an overlay to the static support on the mobile device's screen (figure 9.6).

The overall price tag of SPART-ME D V1 I3 is 90 € (June 2024, France) (potentiometers, battery, Analog-to-digital converter chip and microcontroller). Performance-wise, the mean error is 0,5 cm. Figure 9.8 shows the distribution of errors for positions every 5 cm for a surface of 50 x 40 cm (left to right: X Error, Y Error, Euclidian distance). The diagram reveals where the prototype design has its lowest accuracy: Between the potentiometers and far off, when change in position translates to small relative changes between unwound strings.

The prototype performs well in respect to fluidity (30 Hz), robustness and covered range (A3). Its use in multi-device settings is limited to two devices (but problematic due to the four strings involved), being attached to a solid support does not make for a very

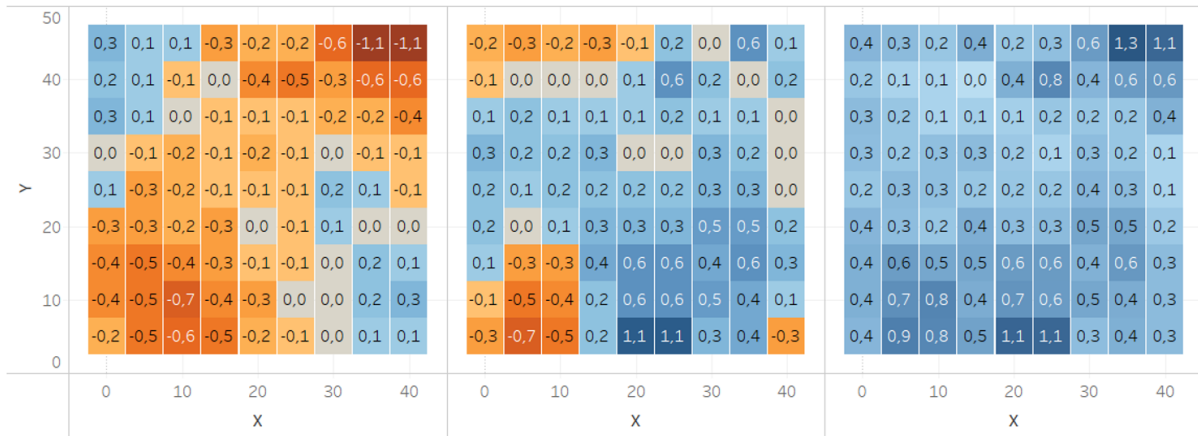


Figure 9.8: Mean error results by distance from potentiometers: errors in x direction (left), y direction (center) and Euclidian distance (right)

good mobile experience (700 g and bulky) and accessibility is limited (price tag of 90 €). Nevertheless, we were confident that these limitations could be overcome and reach the predicted score of 8 predicted in chapter 8.

Table 9.5: Evaluation of the first version, third iteration of SPART-ME

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-ME D V1 I3	1.5	1.5	1	0.5	1	0.5	0.5	0.5	7

9.4.2 Improvements

Improvements to SPART-ME D V1 resulted in a V2 version (SPART-ME D V2 I1 and 2). For this prototype we chose a microcontroller based on the nrf5280 chipset with 12 Bit integrated analog precision (SEEED XIAO nrf52840) to avoid the use and soldering of a dedicated analog to digital chip. The use of this chipset brought down the price from 90 € to 70 € and increased accessibility (reduced soldering). Furthermore, we used rotary encoders, an alternative way of measuring the rotations of the string reels. Commercially available, cheap rotary encoders typically function through physical contact with internal metallic disks and have a precision of 15 degrees. This means that a mechanical transmission is required to increase precision. However, transmissions to increase the rotation

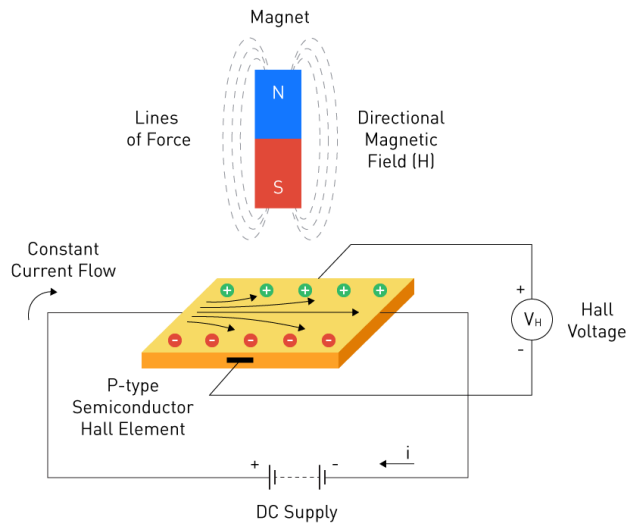


Figure 9.9: Hall sensor principle: the magnetic field pushes electrons perpendicularly to the electric current direction resulting in a Hall voltage across the conductor. Illustration by [Monolithicpower](#)

of the encoder axis result in a stronger required torque to turn the measuring axis, and by consequence, a stronger retraction mechanism for the string. In our initial design, the tablet was already retracted when not held back at positions of around 30 cm from the potentiometers, which make this approach impracticable. Instead, we opted for the devel-

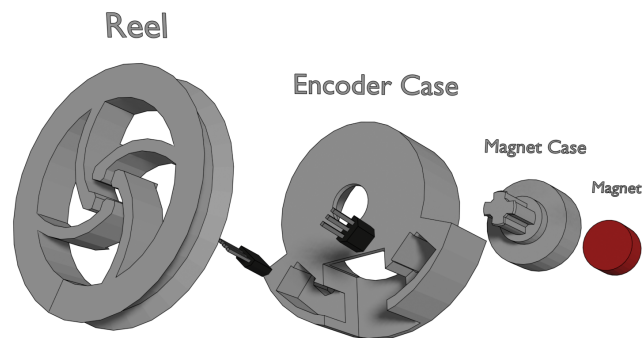


Figure 9.10: A 3D printed high precision magnetic rotary encoder based on two S49E analog Hall sensors (black) and a magnet (red). Cost: 2 €

opment of magnetic rotary encoders. Magnetic rotary encoders measure the variation of field strength from a magnet fixed to the measurement axis. Magnetic field strength can be measured through Hall sensors. Hall sensors are based on the Hall effect, occurring on

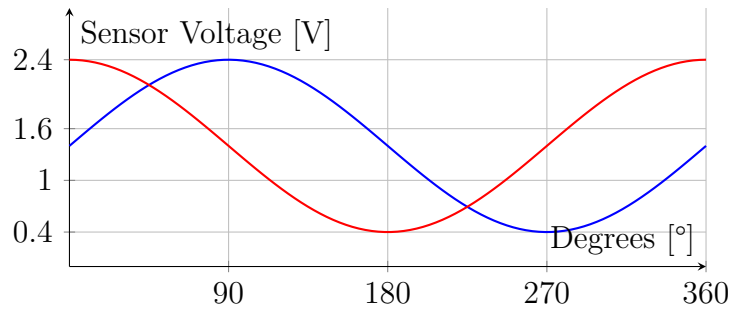


Figure 9.11: A rotation of a round magnet between two 90° spaced Hall sensors (red and blue) results in sine wave voltage levels

conductors like metal plates connected to an electrical circuit and exposed to a magnetic field. Mobile charge carriers on the conductor experience a force from the magnetic field, deviating them from their path, which results in a change in voltage across the conductor, called Hall voltage (figure 9.9). With a round magnet, diametrically magnetized, two analog Hall sensors can be positioned at a 90° angle (figure 9.10) and the result of a rotation are sinusoidal graphs (figure 9.11).

This design has multiple advantages compared to potentiometers and commercially available rotary encoders: unlimited range, combined with 3D printing material (PLA or ABS) negligible friction, meaning retraction mechanisms do not have to provide high torque, and a very low price tag (2 € with SS49E Hall sensors), given the high accuracy.

Replacing the potentiometers in the initial design, this amounts to a price reduction of 35 €, bringing the total price for the prototype to 20 € (+affordability). This increase in accessibility increases the score of SPART-ME D in its V2 to the estimated 8 points in our technology review (table 9.6). The estimated score of 8 has notably been achieved



Figure 9.12: Soldering of two S49E Hall sensors (left) for use in the assembled rotary encoder (right)

due to the use of custom rotary encoders. To address the remaining issues of mobility and multi-device usage, we developed a final version of SPART-ME relying on an alternative localization technique.

Table 9.6: Evaluation of the second, improved version of SPART-ME D

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-ME D V2 I1 & 2	1.5	1.5	1	0.5	1	1.5	0.5	0.5	8

9.4.3 SPART-ME Mono String

The development of low friction magnetic rotary encoders for the mechanic prototypes of SPART, allowed for a new prototype: SPART-ME M (Mono string). SPART-ME M relies on a hybrid design. A single string is used and its length and angle are measured (angle measurements along strings require very low torque rotary sensors to yield accurate measurements). Geometrically, the known position of SPART can be considered the origin

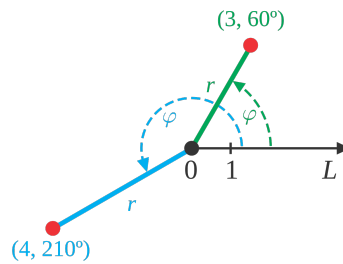


Figure 9.13: A polar coordinate system based on angle and distance to the origin. Illustrations by Monsterman222 (Wikipedia user)

of a polar coordinate system (figure 9.13). Polar coordinates (as opposed to Cartesian coordinates) are defined through an angle and length to the origin (pairs of length and angle). The polar coordinates can easily be converted into Cartesian coordinates (see equation 9.3).

$$P(x, y) = (r \cdot \cos(\varphi), r \cdot (\sin\varphi)) \tag{9.3}$$

Figure 9.14 shows SPART-ME M V1 I2: One rotary encoder is placed on the reel axis, while the second one measures the angle of an arm through which runs the string. The arm follows the string and can thus detect the relative angle. As can be seen in this first prototype, shielding was required to isolate both magnets from each other (otherwise, magnets would act on each other at such distance). To address the problem of mutual interference (both in sensor readings and rotation of the axis itself) we settled for smaller, rectangular magnets (since small round magnets are not commercially available) with non-circular magnetic fields, impacting the accuracy of measurements for version 2 of the prototype.

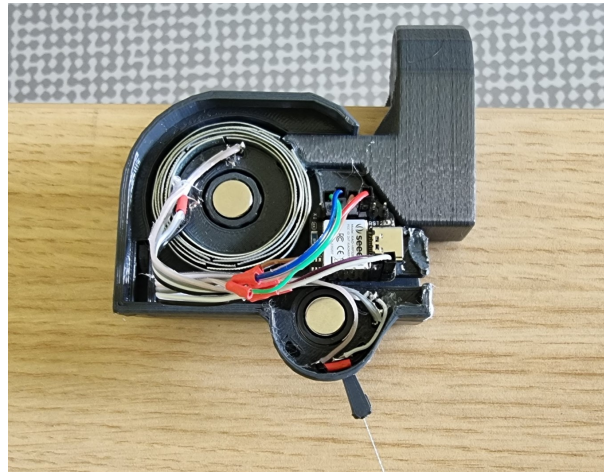


Figure 9.14: Early prototype integrating rotary encoders in a compact design. Magnetic shielding is required to reduce inference between the two encoders

An initial calibration of magnets is required: the creation of a mapping between the arms angles and sensor values. In turn, interference does not take place. We housed the components in a modular 3 stage design (figure 9.15). The bottom part contains the reel and the power switch. The middle part houses the battery, microcontroller and rotary encoders. The top lid can be customized with buttons, additional sensors or microcontrollers that can be linked to the main chip through a standard four line I2C data bus. This aspect allows easy customization depending on user needs. It is also removable through a screw mechanism. Detailed illustrations can be found in Appendix B. Assembly (illustrated in figure 9.16) starts with the reel consisting of two parts. Part ① is printed separately to take advantage of 3D printers' ability to print a smooth first layer without imperfections that would hinder the spring rotating. This part is later fixed on ③b and ⑤d . The axis ①a later rotates in ⑥c where a 5 mm cube magnet has to be mounted with its

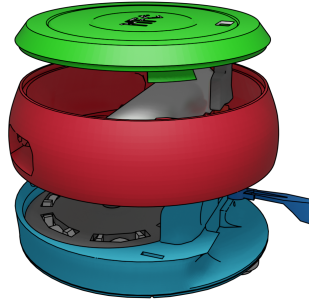


Figure 9.15: 3 stage design of SPART-ME M

north/south pole being oriented laterally.

Part (1) can be connected by applying pressure onto part (3). Several small mounts (3a) fit holes in part (1) and use limited elasticity of 3d printing filament to tightly attach (1) to part (3). A spiral spring can then be inserted into the hole in part (3). A string with diameter <0.2 mm has to be wound on reel (3) and can be attached through a small hole in its shell. The end of the string has to be passed through a tunnel under part (5) and through its small head. Part (5) consists of the guiding arm with a small hole and the axis in which the second magnet has to be placed. The combined piece of part (1) and part (3) can then be placed into part (4) with the spiral spring fixated on the hinge (5d). The string can then be put under tension and a paper clip attached to its end to avoid the string to get unrolled back into the tunnel of part (4). This version features a printed switch (2) which uses paper clips housed in space (5a). Figure 9.17 shows a detailed view of the switch mechanism. The switch (2) slides on the outer shell and has a rounded inner side (2a) which allows it to push paperclip (8a) towards (8b) until both touch and close the circuit. Paperclip (8a) also stops switch (2) from accidentally closing the circuit. Elasticity of paperclip (8b) allows to exert constant pressure on paperclip (8a) and assure a reliable electrical connection. To both paperclips are then soldered jumper cables, since this part passes through holes in (figure 9.16 (6)) and must be allowed to disconnect in the event of disassembling the device (e.g. for reparation). Part (6) can then be placed on (5). Mountings (5a) stick through the bottom of part (6). The guiding arm (5) has to be inserted in hole (6d). The irregularity in the hole shapes accounts

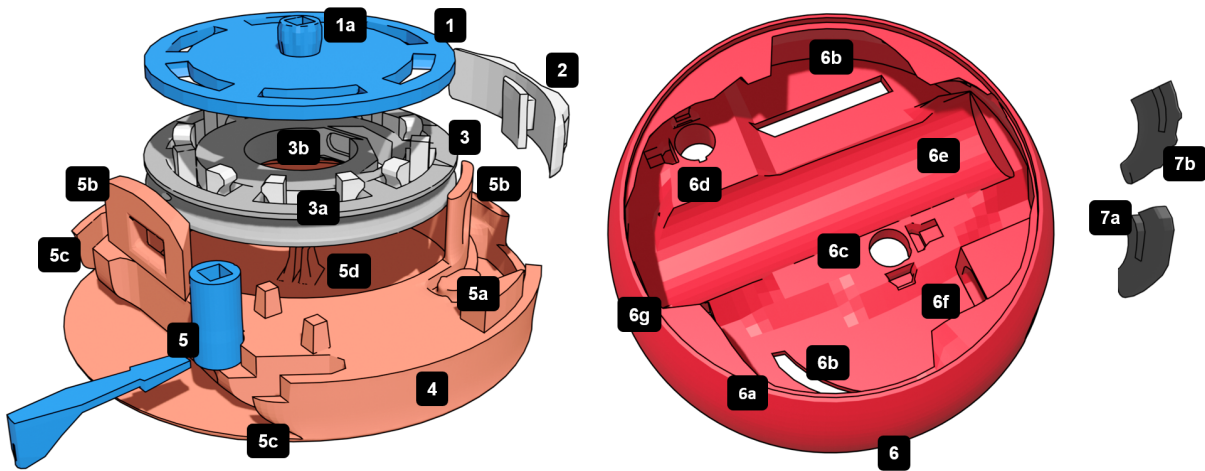


Figure 9.16: Bottom and middle part of the second prototype iteration

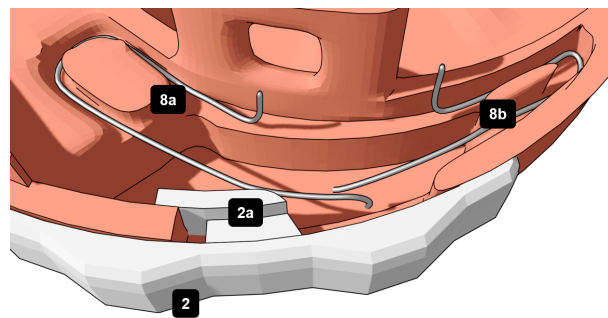


Figure 9.17: SPART-ME M V2 3D printed power switch with a paperclip

for the characteristic printing imprecisions in Fused Deposition Modeling printers called seams which occur when the printhead starts and stops printing an outer surface layer. Leaving a crevice prevents blocking of (5) which requires minimal friction in order for the positioning results to be accurate. Parts (7a) and (7b) can now be pushed into the holes of (5b). Crevices allow to push part (5) against (6). The rugged back of (7b) increases friction with part (6) due to the 3D printing process of incremental layers which leave a rugged vertical and inclined surfaces on a macro level. The battery compartment is sized for a standard 18560 LiPo 3.7 V battery and at part (6f), a small micro-controller like the Seed nrf52840 can be clipped into the shell (6), with its USB port pointing through the hole in the shell for manual debugging via USB. The internal circuit is simple: the four Hall sensors of the two rotary encoders are directly connected to the micro-controller (figure 9.18).

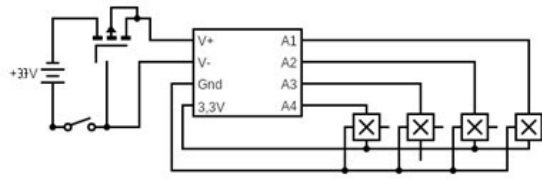


Figure 9.18: SPART-ME M circuit design. Four S49E sensors are directly connected to the microcontroller (right). The circuit features an inverse circuit battery protection through a Mosfet transistor and power switch (left part)

We added a Mosfet transistor in later versions for a simple protection circuit of the battery and a power switch consisting of a paperclip. The whole prototype can be printed and assembled without glue and can thus be easily repaired or parts replaced when required. The software uses a GATT Bluetooth Low Energy (BLE) architecture. It exposes two services, one for the provided position, updated on every change, and one for the custom shield (currently only NFC). In the main execution loop, the angles are retrieved from the rotary encoders and complete rotations of the reel are detected (for each passage from 0° to 360° and vice versa). Both length and angle are passed through a low pass filter to reduce noise. If a threshold for a new angle is surpassed, the position is calculated. As for the NFC chip, the update rate depends on a custom setting to reduce battery consumption. Given the error due to the form of the rectangular magnets, a corrector function is added to each angle measurement. The code can be found in Appendix C. The mean error of SPART-ME M V2, if calibrated manually, is currently 0,2 cm measured on a surface of 20 x 40 cm.

Figure 9.19 shows accuracy with a single Hall sensor on the guiding arm and limited to 150° . Calculation speed exceeds 30 positions per second. The prototype has a weight of 300 g with a LiPo 18560 battery and has proven robust during a combined use of 12 hours. Over time, yarn string shows signs of wear out and finally rips. We recommend the use of fishing line. Material cost for a mobile version of this prototype (battery included) can be produced for around 20 € as of 06/2023. An ESP32C3 microcontroller can be purchased for 6 €, a Samsung LiPo 18650 battery for 5 € and four Hall sensors at 1 € when bought in bulk. Badges to harvest spiral springs from, can be bought at 2 €. Required cables, electricity and printer filament account for 5 €. Building the prototype requires a minimum of soldering, operating a 3D printer and assembly. Soldering can be reduced if Hall sensors are delivered soldered to the board. The modularity of the latest version of the prototype

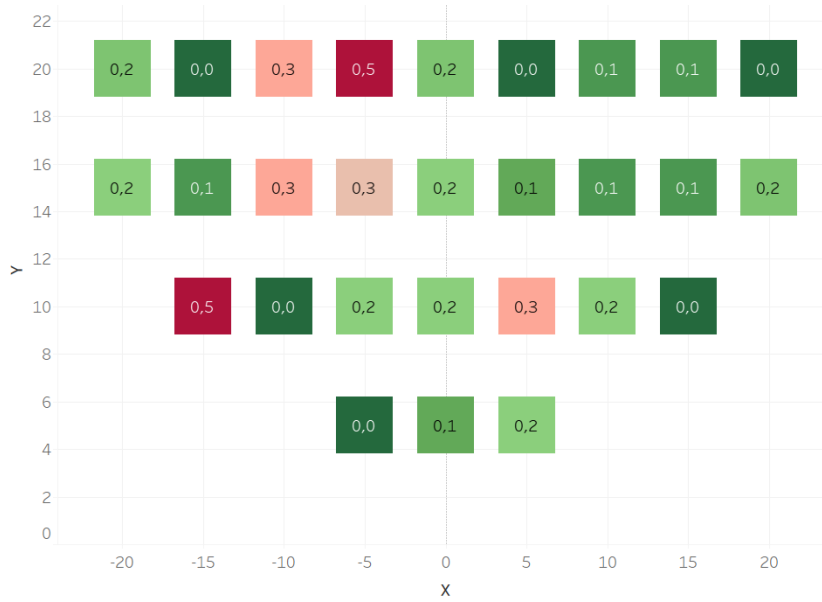


Figure 9.19: Mean error (Euclidian distance) for positions around the origin of a single string prototype

allows to replace individual broken parts easily. This prototype supports four devices on a single surface (a higher number could be feasible but entanglement of strings is likely to occur).

Table 9.7: Evaluation of SPART-Me mono string

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-ME M V2 I5	1.5	1.5	1.5	1	1	1.5	1	1.5	10.5

Finally, compared to the first SPART-ME D prototype, this version of SPART improves on the aspects of affordability, mobility, robustness and the possibility of a multi-device setup. These improvements lead to a final assessment of 10.5/12, making it a good candidate for mCSCL setups.

9.5 SPART-VIS: Concepts Based on Computer Vision

As figure 8.5 in chapter 8 shows, electromagnetism, especially for wavelengths in the visual spectrum has led to positioning techniques, most prominently, marker and markerless tracking technologies. The technology has matured to the point where it can be used across different device types and models, requiring only a camera to work. We considered a setup where one smartphone would track another, either through displayed markers or a markerless approach (figure 9.20). The problem however is the low angle of the second smartphone's camera which does not allow for tracking without an additional stand (making the approach not only costly, but also reducing mobility). Furthermore, using computer vision in environments with differing lighting conditions (shadows of trees etc.) remains a challenge.

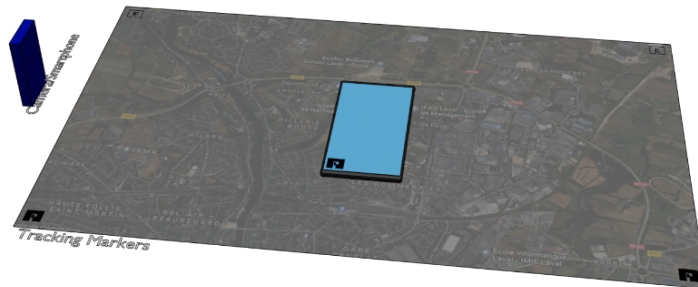


Figure 9.20: Visual tracking concept through a second smartphone

Similarly, technologies like CIS shadowing, light triangulation and IR angle of arrival all require substantial electronic circuitry and investment all while being confronted with interference issues from sunlight (as does the previous approach). Using the back facing camera of a smartphone might be viable in inside environments where the ceiling can serve as a reference, but in outside conditions, moving objects (e.g. clouds) and missing reference points make this approach unreliable. Redirecting the camera's field of vision through mirrors back onto the map is no viable option either, since the fixed focus of these cameras is typically an arm's length.

The only remaining, robust enough configuration (figure 9.21) necessitates isolation

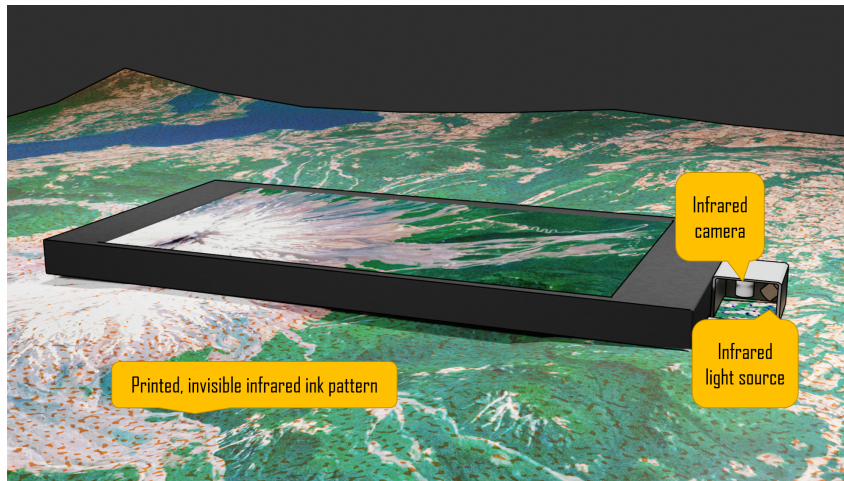


Figure 9.21: Infrared ink pattern concept : A small module powered by the phone’s USB port reads an invisible code pattern on the surface

from outside interferences in a close up camera setup where an external CMOS sensor is attached to the phone with a diode to illuminate the surface. The surface is covered with infrared ink codes that can be read by the sensor. Such technology is used in “speaking pens”, used in products to help children read. However, infrared ink is not widely available for printers, making this approach uninteresting for widespread use. Furthermore, the CMOS circuits are not commercially available (-DIY).

9.6 Overall Assessment of the Developed Prototypes

Among the developed prototypes, only mechanical versions proved reliable. Magnetic and acoustic versions did not live up to the expectations grounded in our technology review. In turn, the mechanical variants, beyond the caveat of physically attaching these prototypes to the mobile device, performed well in our field studies. The design of SPART-ME M V2 also allows for the development of a variant for 3D localization by adding another sensor and axis to the arm component and for the integration of additional entry points through sensors within the top part (e.g. NFC antenna) without the need to redesign the entire prototype itself. Table 8 summarizes the evaluations of the different versions of SPART.

Table 9.8: Summary of SPART prototype evaluations, ordered by total score

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
SPART-ME M V2 I5	1.5	1.5	1.5	1	1	1.5	1	1.5	10.5
SPART-ME D V2 I 2	1.5	1.5	1.5	0.5	0.5	1.5	1	1	9
SPART-ME D V1 I3	1.5	1.5	1	0.5	1	1	0.5	1	8
SPART-MA B V1 I3	1.5	1.5	0	1.5	0.5	1.5	1.5	1.5	0
SPART-MA C V1 I3	0	1.5	0	1.5	1	1.5	0.5	1.5	0
SPART-MA BR V1 I3	0	1.5	1.5	1.5	0	1	1	1.5	0
SPART-AC V1 I2	0	0	1	0	0	0	0	0	0

9.7 Conclusion on SPART Prototype Design

In this chapter we presented magnetic, acoustic and two mechanic prototypes to implement the interaction SPART (SPART-ME). Figure 9.22 summarizes the results of the previous state of the art and our prototype developments and evaluation alongside the process results first outlined in figure 8.1 of chapter 8.

Albeit the limitation of a physical connection to the device, both mechanic prototypes fulfill the list of requirements established in chapter 8. As of the time of writing (07/2024) magnetic and acoustic prototypes are not functional for the use in field studies due to issues of range, robustness, fluidity and accuracy. The mechanical variants though, can be used in future studies with horizontal peephole interactions. In the following part of this dissertation, the prototypes SPART-ME D V1 I3 and SPART-ME M V1 I5 are used to conduct two exploratory studies with middle school students. Optical variants, which seemed promising at the technology review stage, turned out to be impractical in terms of sensor availability and robustness.

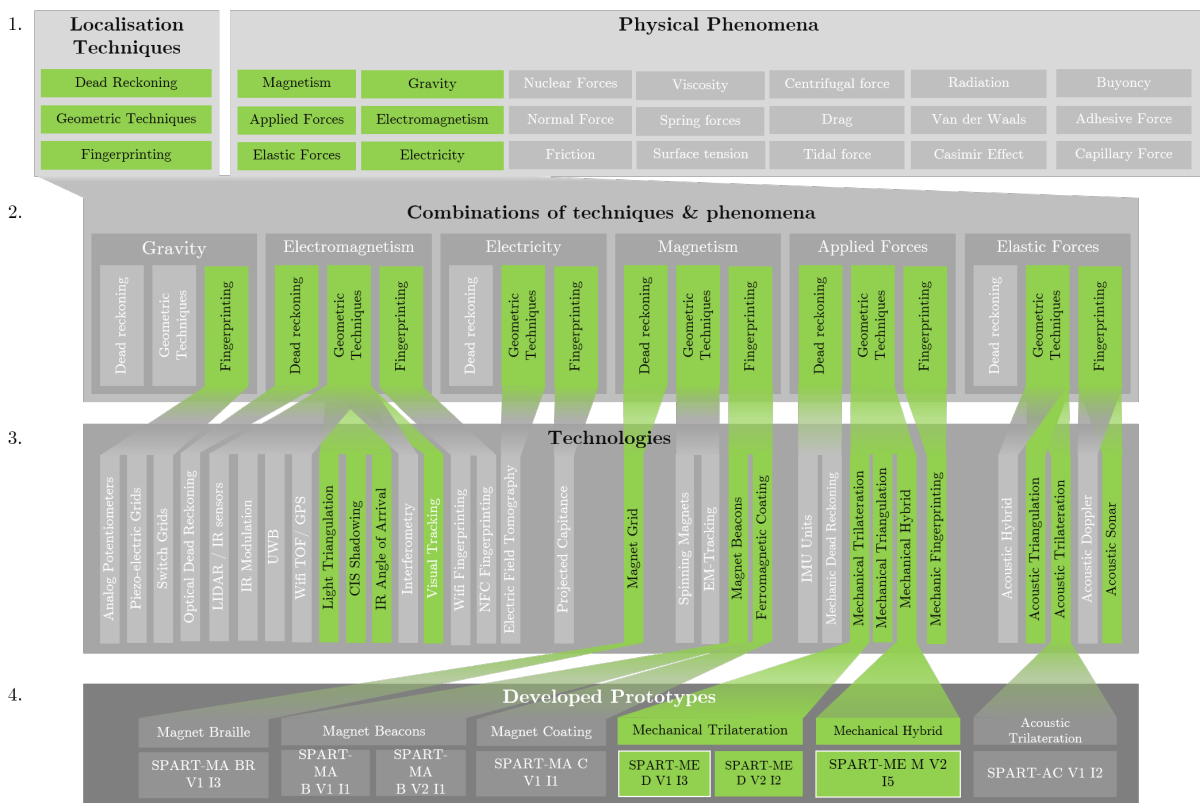


Figure 9.22: State of the art and prototype development results. Prototype labels: BR – Braille, B – Beacons, C-Coating, D-Dual string, M-Mono String, V+number: Version, I+Number: Iteration. Outlined prototypes have been used in field studies. In green: prototypes/technologies/phenomena/techniques fulfilling the requirements

HARDWARE PART SUMMARY

This part of the dissertation has been dedicated to the process of identifying and implementing the novel interaction type **SPART**, a horizontal dynamic peephole interaction. To this end, we firstly presented **literature of existing mCSCL supports** in chapter 5 (figure 4.11:1), resulting in the observation that, while technology is developed to create a mobile large workspace, the research on the type of interaction that best suits the different approaches is scarce. Consequently, we defined criteria for interactions with low inherent cognitive load, a major aspect to support collaboration (itself drawing on this resource). The four identified criteria for interactions (fidelity, accuracy, feedback closeness and interaction realism) led us to identify SPART as particularly promising. Thus, in chapter 7, we introduced the **design methodology** enhanced by aspects of **open science** to complete a list of requirements for the technology and conditions under which SPART could be implemented in educational settings (figure 4.11:3): accuracy, fluidity, range, mobility, robustness, affordability, DIY, and multi-device support.

Having defined methodology and requirements, we presented a **state of the art of available technologies** in chapter 8. There, we identified and pre-filtered localization techniques and physical phenomena, before evaluating remaining combinations of both. This set the ground for the identification of technology based on those combinations, which we evaluated against the list of requirements identified in chapter 7. We attributed scores from 0 to 1.5 for each criterion, resulting in possible scores from 0 to 12. Finally, we built **prototypes** off the remaining technologies with a positive overall score from the requirements. Among the 18 attempts, three mechanical prototypes lived up to their estimated scores: two prototypes SPART-ME D with two strings and one hybrid version with a single attached string. The development of the latter has been made possible thanks to our development of a low-cost 3D printed, high precision magnet rotary encoder and the former to the development of low-cost string potentiometers. All developments have given valuable insight into the feasibility and challenges of the different approaches. In the next part, the studies that have been conducted with two mechanical prototypes (SPART-ME M V2 I5 and SPART-ME D V1 I3) are presented and their usefulness for collaborative learning analyzed.

PART IV

Studies

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INTRODUCTION

In the previous part of this dissertation, we described the successful implementation of two prototypes for SPART, a horizontal peephole interaction. These prototypes were tested in **two field studies** and during a **science fair**, the results of which are presented in the following chapters. Both studies were designed in collaboration with middle school teacher Guy Théard. For both studies, he provided us with course material and subjects. Both studies are thus studies combining pedagogical objectives and the intention to study the interactions with SPART. To this end, content and functionality were adapted both to the pedagogical objectives and groupware design. The first chapter will describe the setup, activity, analysis and results of a first field study with 32 middle school students in a geography activity. The second chapter is structured accordingly for a study with 12 middle school students engaging in a field trip-like experience during a biology class. The third chapter will describe a **usability test** with 60 users playing a short history game during a local science fair. Finally, we will present a conclusion to these chapters, outlining the main perspectives of all three experiments. As discussed in the introduction, the focus of our studies is the role of the tool for collaborative processes (as opposed to the learning outcomes). As such, both studies are of exploratory nature to determine which collaborative aspects are likely to be supported by SPART. Results of the second and third chapter are yet to be published.

Related Publications

Sebastian Simon, Iza Marfisi-Schottman, Sébastien George. Peephole Technology for Mobile Collaborative Learning: An In-Classroom Exploratory Study. In: *Proceedings of the 16th International Conference on Computer Supported Education (CSEDU 2024)*, INSTICC, May 2024, Angers (FR), France. pp.103-114.

STUDY 1: SPART INTERACTION IN COLLABORATIVE LEARNING

The successful development of the first mechanical prototype, SPART-ME D V1, enabled us to set up a comparative field study conducted to focus on RQ1 (“Does an augmented reality interaction, consisting of a mobile device placed and moved across a static surface, constitute an improved collaborative learning support? If this is the case, how does it influence collaboration?”). The objective was to explore whether SPART was involved in collaborative sequences, and if so, to what extent. Consequently, we designed a study in which eight groups of four students each, aged 12 to 14, would engage in a one-hour activity either with SPART or through a static peephole interaction on a tablet. All interactions were video recorded. We coded and analyzed conversations, gestures and tool interactions. The study was conducted in four sessions in November and December 2022. The activity and software were developed in a design-based research approach in multiple iterations and close collaboration with the student’s biology teacher. The ensuing subsections describe in this order: the context of the activity, the activity itself, procedure and analysis. We finally present the results, limitations and end this chapter with a conclusion.

10.1 Context

French middle-school students, between 12 and 14 years old, are confronted with the theory of **tectonic movements**. Such content can be conveniently adapted in a collaborative activity, given that the theory of tectonic plates’ movements has historically been debated for a long time: It first emerged in the late 1800s and was questioned until the 1960s (H. R. Frankel 2012). Scientific debate is a formidable carrier of collaborative activities as we have pointed out in part 1, since by definition, it is an exchange bolstered by evidence and typically a wicked or ill-defined problem (justifying collaborative cognitive load). Indeed, only through the continued use of global data about the age of the ocean floor, analysis of changing magnetic field patterns in the earth crust, fossils and seismic measurements could adepts of the continental drift theory like Jason Morgan convince

the attendees of geophysical congresses in the 1950s and 60s of the continental drift theory. This theory states that continents moved over billions of years over thousands of kilometers into their current position (H. Frankel 1990).

10.2 Activity Design

In order to provide room for collaborative learning, as defined by Stahl (2006), we structured the activity in several tasks with fading scaffold. Students¹ were handed a description of the scenario containing four distinctive tasks and optional hints at the end (appendix D). In this fictional scenario, students found themselves in the role of research assistants of geographer Jason Morgan in the 1960s. About to present his theory of tectonic plates in front of the national geophysical congress, the overall task consisted in giving J. Morgan compelling arguments to convince the skeptical congress attendees (known historically as “fixists”, arguing against continental drift). To that end, students were given data of

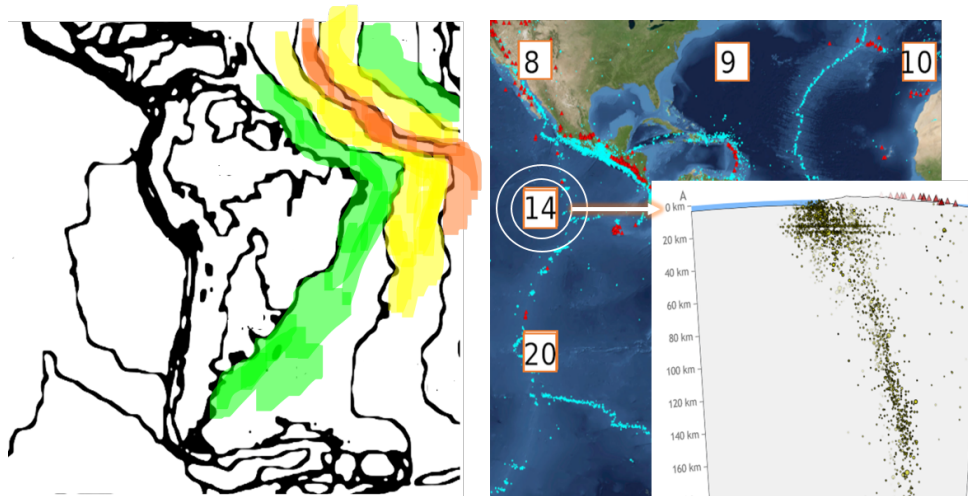


Figure 10.1: Maps for the activity in study 1: Ocean floor age overlay (basemap), partly colored (left), seismic activity overlay with profiles (right).

ocean floor age and seismic activity graphs (figure 10.1) to deduce direction and speed of tectonic plates from. In order to encourage collaboration, we added elements of positive identity interdependence (research teams), positive fantasy interdependence (the back-story features Harold Jeffreys, a prominent critic of the tectonic plate theory), and an

1. We'd like to express our gratitude to Guy Théard and his students for testing our prototypes.

ill-defined problem (“find evidence to prove a theory”), which provides cognitive reason (since it cannot be solved by an individual) to collaborate (Koschmann 1996).

The activity was structured in four tasks: Initially, groups had to read and understand the assignment. The second task consisted in coloring the map depending on the ocean floor’s age (figure 10.1, left). Thirdly, students explored the seismic graphs (seismic data in vertical cuts through the earth’s crust) by classifying them depending on seismic intensity. Finally, students had to define the direction of the plates’ movements and explain “incoherent” ocean floor data in front of the coast of Chile (old and recent plates side by side). For this to succeed, students had to digest hints, spatial data and emit hypothesis they would (in-)validate with the available data to provide Jason Morgan with a speech on evidence for the relative movement of tectonic plates.



Figure 10.2: A SPART group during the coloring task.

Students were provided a static map containing the outlines of geographic ages, coloring pens and paper based vertical seismic data for a number of fixed positions (figure 10.1, right) alongside a map with the age of the ocean floor layers printed on it (figure 10.1, left). This data was also accessible through the tablet application through a peephole interaction. Students could therefore pick their preferred medium. Appendix D contains the activity assignment handed out to students with its appendices. Groups with the dynamic peephole interface (named “SPART” groups) had the layer map attached to

a rigid support to provide accurate overlay (as in figure 10.3 (4)), whereas groups with static peephole interactions (“Control” groups) were given a tablet and the base map separately. The application on the tablet (Samsung Tab A9, 19,3 x 10,8 cm) provided two overlays that could be changed with the click on a virtual button (also sketched on the static support): one with numbers about the age of the ocean floor, and another with the seismic activities (see figure 10.1 right). On the second overlay, students could access the vertical profile of seismic activities at specific positions (see figure 10.1, right) by clicking on the screen position (indicated by a button). In the paper version, the vertical profiles had to be looked up on a separate sheet. During the first two sessions, none of the groups managed to complete the activity. Consequently, we introduced additional hints in the task assignment.

10.3 Indicators and Conceptual Underpinnings

We used the PAC framework, presented in part I, to analyze the video material of the experiment. We identified several indicators for participation, awareness and coordination:

Participation

1. Positive indicators: balanced verbal participation and actions, transactive discourse, promotive interactions (DiMicco *et al.* 2004)
2. Negative indicators: difficulty for one participant to engage with others and the tools, visible hierarchies among team members (Pierre Dillenbourg 1999)

Awareness

1. Positive indicators: reference to other’s knowledge (cognitive awareness) and seamless transitions in action sequences (behavioral awareness).
2. Negative indicators: demanding clarification on actions (behavioral awareness), asking about who could know what (cognitive awareness), asking about emotional states (social awareness) and questions about the state of the work space (work space awareness) (Karaoglan Yilmaz and Yilmaz 2019).

Coordination

1. Positive indicators: providing information, disagreement to information, making plans, planning, discussing plans, group processing (revising strategies based on available resources) and resource sharing. (D. W. Johnson and R. T. Johnson 2009)

2. Negative indicators: absence of strategies, paralyzed groups, difficulties during coupling transitions

In addition, as a means to explore whether SPART induced considerable cognitive load, we considered the number of times students tried to navigate the SPART tablet through gestures instead of moving the device (the predominant interaction type with tablets and mobile devices).

10.4 Procedure

For reference, we label the different groups group 1 to 8 and specify in brackets whether the group has used SPART or a static peephole interaction. Groups 1 to 4 are groups having used SPART and groups 5 to 8 have used the static peephole interaction (control condition). Numbering does not reflect any ranking and is dedicated to labeling only.

Due to lesson restrictions groups 1, 2 and 4 (SPART condition) and 5, 6 and 8 (Control groups) had 60 minutes, while group 3 (SPART) and group 7 (a control group) only had 45 minutes for the activity. Group composition was orchestrated by the teacher in an effort to create homogenous groups in terms of task performance. Groups 1, 3, 4 (SPART), 5, 7, 8 (control condition) were mixed groups (two boys, two girls). Group 2 (SPART) consisted of four girls while group 6 (a control group) consisted of four boys. The classrooms, as illustrated in figure 10.3, are structured in work islands (3) that allow students (7) to stand, or sit on elevated chairs. Students in this study were standing, aligned and facing one of two cameras (1), (2). We filmed from two angles: One camera faced the group to capture facial and gestural expressions (1) while the second camera (2) targeted the table to record interactions with the workspace.

At the beginning of each experiment, participants were shown the tablets' functionalities (6) and were given a short introduction to the activity. Every group had a tablet, a copy of the task assignment with all map layers printed in color, as well as seismic data printed as graphs for specific locations (as in figure 10.1, right). All information was available on paper and on the tablets for students to use either or both in parallel. At the end of the experimentation, students were asked whether the group had worked together before and about their perception of SPART during the activity. Additionally, having identified one high-performing group, we interviewed the most engaged student on his experience in a 30 minutes' session. During the interview, he was shown video extracts of the experiment and was invited to describe them before being asked more targeted

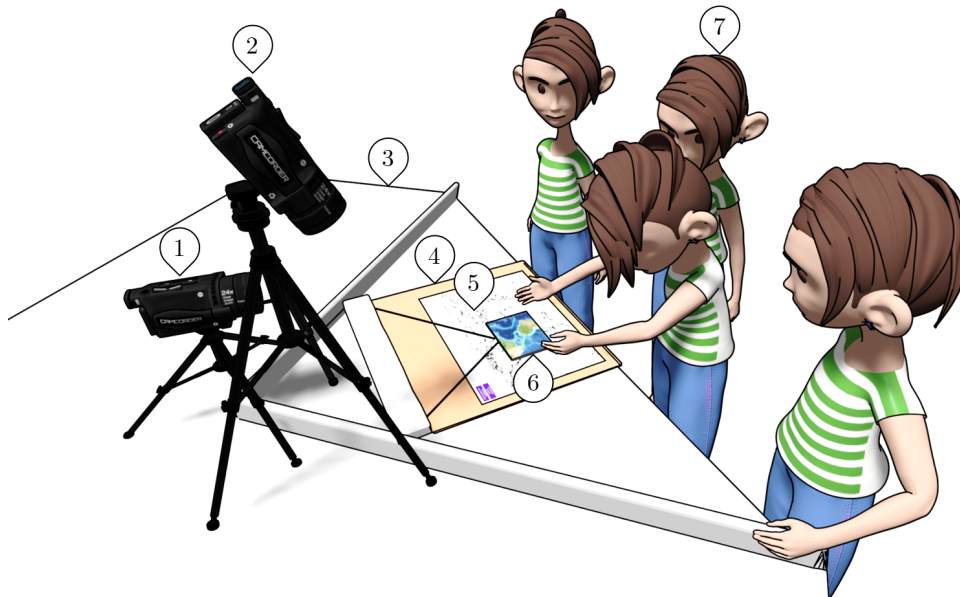


Figure 10.3: Cameras and experimental setup (SPART)

questions (e.g. “What was your intention behind this move?”).

10.5 Results

In this section, we analyze video material with an emphasis on the 3 PAC processes. We also highlight contributions to the social space, as collaboration often fails without (Bannon 2006), and contributions to the cognitive space. Analysis has been carried out by transcribing the videos and identifying collaborative sequences through the use of the previously mentioned indicators.

10.5.1 Participation

In terms of oral contributions, we measured subject related utterances per group. Group 4 (SPART) had 30% more utterances than the other groups and balanced participation. Group 7 (control condition) showed a fully asymmetric participation pattern in the first half of the experiment: Only one person was working and monopolizing resources (tool access and space). Girls in group 8 (control condition) contributed considerably less than their male counterparts, both in terms of oral and nonverbal participation. The discrepancy in participation was accompanied by monopolization which manifested in one of the boys taking the tablet and interacting with it separately from the rest of the group

(confirming the results of Klinkhammer et al. (2018) who observed the transformation of a shared tablet into a personal device in their experiment).

Participation in group 1 (SPART) and group 5 (control condition) was unbalanced: the first half was completely dominated by the two girls and the second half by the two boys. Interactions in group 2 (SPART) were characterized by participative symmetry but little oral contributions. The overall median value did not significantly vary between Control and SPART groups (Mann-Whitney U test).

In general, due to the limited space around the table, one group member was consistently limited in his/her access to the tablet (Control and SPART). Interestingly, in groups with hierarchies, the person excluded was consistently the same whereas in low hierarchy groups (e.g. group 4, SPART condition), students made way for each other depending on individual needs. In the interview, awareness for the lack of space and tool access was confirmed by the participant, adding “. . . it is important for everybody to equally access the tool, everybody should have a turn on it”. Beyond awareness for the importance of equity in participation he stated that he regularly took an active role in regulating access by pointing out unbalanced access to resources. “This was not the case in this activity. I remember talking a lot, B talked a lot, the others were a little more passive, but I think everybody had the possibility to participate”.

10.5.2 Awareness

SPART seemed to work as a visual cue for group members engaging in personal work or activities unrelated to the main task. Indeed, having interviewed one of the students of group 4 (SPART), the student outlined the role of SPART to follow his team member’s activity at a distance, both during phases of cooperation and transition back to collaborative phases. In group 1 (SPART), two boys got carried away by a discussion about computer games (figure 10.4). However, at least one of the two regularly had a glimpse at SPART. After twenty minutes, the two girls decided they had invested enough effort and ordered the boys to do the remaining exercises. Interestingly, the boys were aware of the exercises’ results carried out by the girls and were able to conduct the following tasks without re-iterating over the previous work.

Inversely, in group 8 (control condition), monopolization of the device was an issue, since other group members temporarily couldn’t follow one group member holding the tablet in his hands while walking around. Similar situations arose when members held the tablet (in control conditions) in a specific direction, thus blocking access of other mem-



Figure 10.4: Girls working with SPART while boys converse off-topic (yellow: tablet position)

bers (groups 6,7 and 8, control condition). In addition, we noticed that the strength of the SPART retraction mechanism required students to hold the tablet in position. While not ideal in tool usage, members helped each other holding the tablet in place and manipulating it conjointly. group 4 (SPART condition) showed consistently recurring **behavioral awareness** as two or three members of the group interchangeably manipulated the tablet to move it into position, displaying profiles and changing layers.

Cognitive awareness was rare: Group members sparsely referred to their peers' skills or knowledge. Group 4 (SPART) was an exception in a sequence where one of the boys (A) remembered a previous lesson and another group member (B) remembered that A had kept a cardboard model of a tectonic plate movement that they introduced to refresh and illustrate knowledge about tectonic plate movements. Concerning **social awareness**, groups globally functioned well in terms of timing for oral interventions except for a member of group 4 (SPART) who occasionally tried to contribute his ideas at the same time other members were talking. When he was the only one talking, peers sometimes did not react to his propositions or ideas.

10.5.3 Coordination

Among the eight groups, little coordination (e.g. changing strategies, searching for missing information), beyond linearly following the exercises, was found. group 4 (SPART) was an exception and also the only group to correctly identify lateral and vertical tectonic plate movements as well as differences in speed (thus successfully completing the assignment).

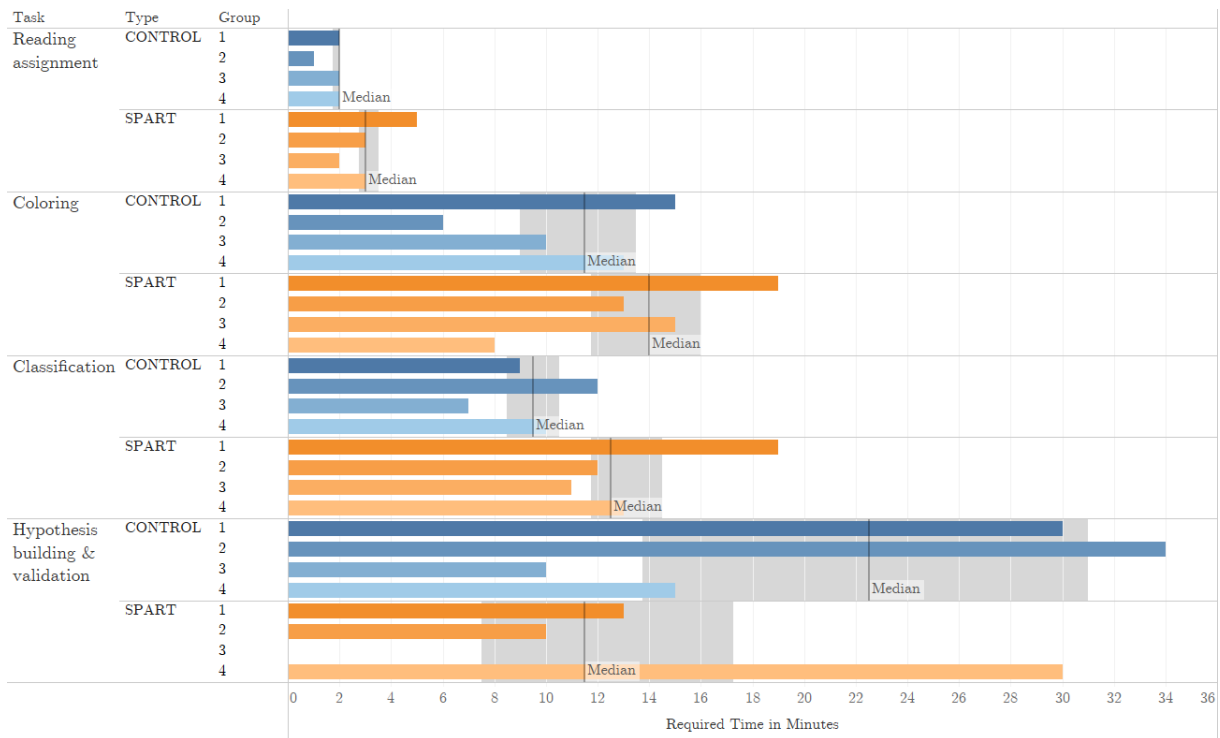


Figure 10.5: Time spent by SPART-groups (orange) and Control groups (blue)

Group 4 (SPART) showed signs of awareness for the potential limit of time and tool access. Two students proposed to advance individually on follow-up exercises during the coloring activity, after noticing that the coloring activity could be conveniently carried out by two students (“...You can be two at coloring together”, *steps away from the table and joins partner in reading next task*). When stuck, the group decided to rebuild common ground by rereading the initial, global assignment and by reconsidering all previously collected evidence following suggestions of the interviewee. When the interviewee was asked about the early parallelization of work, he stated that he commonly employed the strategy in group works to “gain time”. And that “there was not enough space for everybody around the table anyways”. Among the other groups, such behavior was not observed. In control groups and SPART groups alike, the tablet itself did not seem to play a major role for this collaborative aspect. SPART introduced a coordination difficulty for the coloring task in that SPART groups using the attached map for coloring had to move the tablet out of its position where the age of the layer was indicated when coloring the underlying layer at the same position on the map.

SPART groups spent overall more time on the coloring and classification tasks com-

pared to control groups, confirming the time overhead in the integration of the tool into the activity (figure 10.5). Consequently, those groups had less time for hypothesis building and validation, with the exception of group 4 (SPART), having spent significantly less time coloring than other SPART groups. This group used a separate, smaller map with the age of the ocean floor printed on it for coloring, eliminating the need to move the tablet repeatedly. Contrary to our interpretation of a particularly smart use of this second map, interviews revealed that the group initially believed the map attached to SPART was only intended for illustrative purposes. Group 1 just marked the color of a layer with a stroke once, using the tablet, before coloring the whole layer without using the tablet afterwards. This approach avoided the tablet being in the way of coloring (as encountered by group 2 and 3). The group however was not able to turn its approach into a time advantage due to meticulously coloring the entire map afterwards. While SPART groups were slower in completing the tasks, there were little problems with the interaction itself. The interviewee described the interaction as “natural” and “simple to use”.

Occasionally, users tried to drag the overlay with their fingers before remembering they had to move the tablet instead. This occurred on average 1.5 times per group. A difficulty we noticed was that users had to hold the device in order to prevent it from sliding towards the reels (dragged by the spiral springs attached to the retraction mechanism). We thus hypothesize that the interaction itself is easily learnable and that little additional cognitive load can be attributed to the interaction itself.

10.5.4 Social Space

We noticed asymmetric relationships in group 5, 6 and 7 (control groups) and group 1 (SPART). All of them were present since the beginning of the activity, pointing to existing social discrepancies among students. Student exclusions manifested in restricting member’s tool access, especially in control groups by orientating the tablet away from a person. Group 4 (SPART) showed a balanced social space: Members showed motivation, joked while staying task-focused or made fun of each other without demeaning overtone. In this environment fell the brainstorming phase about lateral tectonic plates’ movements which resulted in the correct hypothesis (and its validation): Just before one of the students emitted the theory of subduction in front of the Chilean coast, the group at 52 minutes into the activity was missing an appealing theory. Jokingly, another student said “the plates extend so much that it [the older, missing layer] has just disappeared!” other group members laughed, triggering hand movements of another student to mimic an ex-

plosion. Gesturing continued, this time his left hand slid from right to left (as the previous tablet movement) while he said, half seriously “it went underneath. . .”, then exclaiming: “It went underneath!”.

Interactions in group 6 (control condition) initially were characterized by task distribution by the dominant member, occasionally judging team members (“wait! you’re screwing it up!”, “idiot” etc.) or restricting access (“Can I write?” – “No”). During the final phase, all members could propose their hypothesis, but no consensus (nor strategy to achieve one) was found to decide on one common theory. The group did not show transactive interactions or strategies to validate or falsify the hypothesis. The contribution of two students was restrained to reading the assignment. One of them stated that he “didn’t understand any of this”. His statement was not followed by other group members trying to explain the topic to him and his further interventions were limited to off-topic contributions. Good task performance of this group can be attributed to the good individual task performance of the dominant member and the person filming giving advice, which consisted of intermediate task validation concerning plate limits (“You’re missing one”) and correction at 30 minutes as well as motivational speech at 47 minutes into the activity (“you’re nearly there, you are on the right track”). Scaffolding to a similar extent was not observed in other groups (differential bias). The intervention highlights the importance of strategically placed feedback on task performance and motivation, since the group itself did not give positive peer feedback and exhibited asymmetric group relationships. Since this study was conducted in a classroom setting, teacher interventions also happened in group 8 (control condition) after 60 minutes. The teacher intervened on the wrongly placed arrows for horizontal plate movement. Group 5 (control condition) and group 1 (SPART) assisted at a general intervention by the teacher having identified problems of other student groups finding tectonic plate limits and pointing students at seismic activity to correctly identify these limits.

10.5.5 Cognitive Space

The complete loop of emitting, discussing then testing and finally validating hypothesis could not be observed beyond group 4 (SPART). Tablets were however used as tools for hypothesis validation in group 6 (control condition) and in groups 1 to 3 (SPART). Group 3 discovered a complementary feature (implemented and intended for scaffolding a group in case of difficulties) for displaying a gradient map of the ocean floor age on their own and used it to check their own coloring and movement hypothesis. This feature was

later requested explicitly in the interview by a member of group 4 (a SPART group who had not found it). Group 4 (SPART) used the possibility to display vertical profiles on the map extensively to check hypothesis (mountain chains along plate limits, subduction along earthquakes etc.). The following sequence is the sequel to the previous sequence illustrating the discovery of the subduction movement:

- A: ... it went underneath!
- A: that's why there are mountains! [*uses his hands as plates sliding under another*]
- B: [*slides tablet over Chilean coast with age layer overlay*] But look, there is no information at all? [*points at tablet*] I'm sure the plate is somewhere else.
- A: I'm sure this is it. See, there is a mountain chain
- B: Yes that's maybe it? [*Students chatter indistinctively*]
- A: Wait, wait, wait, my theory starts to strengthen [*He moves the tablet over the sketched buttons to change the overlay to the seismic overlay with profile access, then slides it over the South American continent, then opens a profile on the Chilean coast.*]
- A: See, the line ? [*of earthquakes descending diagonally on the graph*]
- B: So the yellow [*colored, recent tectonic plate*] goes under the green [*colored, older tectonic plate*] ...
- A: That's why it disappeared.
- C: Strange. That would have resulted in...
- A: And we could use that to support ... [*He moves the tablet to another profile icon, opens the profile*]
- A: ... this. We can see clearly the line [*of earthquakes descending in depth*] there
- C: But those are the earthquakes...
- A: Exactly! When the plate moves, it creates friction. And thus earthquakes.

To illustrate and identify the speed difference between different plates, the group used a cardboard model from previous lessons. Interestingly, even the colored map was only occasionally used by group 4 (SPART). Instead, group members used the tablet's white ocean floor overlay (figure 10.1 left) containing the ocean floor's age in numbers. When asked about it in the interview, the interviewee explained it by the difficulty of having an additional level of abstraction ("I had to remember what the colors meant") that didn't seem to provide meaningful information to the group. Another mentioned advantage was the size of the overlay with more details than the A4 printed version this group used for the coloring task.

Overall Performance		Participation	Awareness	Category Coordination	Social Space	Cognitive Space
CONTROL	Control1	◐	○	○	○	◐
	Control2	◐	○	○	○	○
	Control3	◐	○	○	○	◐
	Control4	◐	○	○	○	○
SPART	SPART1	◐	●	○	○	○
	SPART2	○	○	○	◐	◐
	SPART3	●	●	○	○	◐
	SPART4	●	●	●	●	●

Table 10.1: Overall Performance by group and category. Full circles symbolize the overall presence, half circles restrictions and empty circles stand for major problems in the category

The differences in groups by categories are summarized in figure 10.1. Full circles for Participation stand for well-balanced and rich interactions. Half circles symbolize assymetric participation patterns and the empty circle symbolizes an overall deficit in communication. Full circles for Awareness mean that awareness was observed (any type) and empty circles that awareness processes could not be observed. Similarly, coordinative actions were either observed or absent. A social space was either characterized by assymetrical relationships and unresolved conflicts (empty circle), one of both (half full circle) or the absence of both. For the cognitive space, we attributed an empty circle to the absence of knowledge building and grounding, a half full circle for attempts of both or either one, and a full circle for both.

10.6 Discussion

Having presented our observations on the collected eight hours of dual-perspective video material, we present, in the following sections, our interpretation of the role of SPART for the observed collaborative sequences during group work. Initially, we examine the role of SPART for core PAC processes. We further explore its possible impact as a memorization and communication support before hypothesizing its role as support to learn how to collaborate and its contribution to cognitive load. Finally, we discuss the activity design and possible improvements. The following subsections describe the possible role of SPART for collaborative processes (awareness, participation and coordination) from the tool perspective, based on the observations presented previously, and its potential beyond

this study.

10.6.1 PAC Processes

Our analysis points towards **SPART supporting behavioral awareness processes and collaborative group dynamics**. Indeed, SPART seems to enact a visual anchor for other group members, both in synchronized collaborative sequences, as well as in settings with subgroups or reflection phases. The tablet's position allows to deduce roughly on what parts the rest of the group is working. On several occasions, we observed students engaging in off-topic conversations and seamlessly picking up their peer's work. We further observed that **SPART seems to reduce tool monopolization** by one member because it is functionally (and physically) bound to the surface it is placed on. Students in the control condition made use of the tablet's mobility to carry it around and thus monopolizing it. We could not find evidence for support on other collaborative dimensions such as coordination or collaborative conditions. If increased awareness led to increased participation or coordinative efforts, this was not noticeable.

10.6.2 Communication Support

Our observation leads us to believe that SPART could support **nonverbal communication**. Indeed, location and movement of the tablet communicate meaning. The position shows the current working area of the group. Moving the tablet underlines the user's intention and ideas on task hypothesis, validation or information retrieval. This hypothesis was strengthened by interactions during the moment group 4 (SPART) verified and validated the subduction hypothesis (and in preceding exercises: identifying limits of tectonic plates, speed of moving plates and hypothesizing about vertical movements). The conversation sequence illustrates the role of nonverbal communication assisted by SPART's visual affordances. It confirms results by Yvonne Rogers *et al.* (2009) who observed that tablets in their experimentation helped students with speaking problems convey meaning. The particular context of tectonic plates would be an interesting topic for a study on the nonverbal affordances of a rigid body force simulation for nonverbal communication in SPART to confirm the importance of nonverbal communication for collaboration.

10.6.3 Memory Support

SPART's particular advantage seems to be the link between location and information (e.g. for fast access of profiles as shown in figure 10.1). Literature suggests that its appeal is rooted in the spatial and gestural memory that the interaction draws on (Kaufmann and Ahlström 2013). Once adopted, information retrieval is fast and focused. As such, it seems particularly useful for use with maps or high-level visualizations. Association of information to locations is used in other contexts such as techniques for enhancing memory capacities (mnemonics): McCabe (2015) has shown the beneficial use of maps for building high capacity mental structures (mind palaces). Such an approach could benefit collaborative activities in the educational sector. We noticed students having forgotten previous lessons on geography who consequently were disadvantaged in the activity. If content can be delivered through collaborative mind walks, this might benefit individual memory retrieval as shown by McCabe (*ibid.*). SPART can assist mind walks by providing access to collaborative artefacts created during previous collaborative activities (photos, sketches etc.) tied to the exact map position for better recall performance (contextualization).

The second distinctive feature SPART allows for, are **overlays, fitting the physical layer**. While this can be achieved with multiple views of the same, printed map, having just a partial overlay in form of a tablet that can be easily moved, increases practicality. Students used and asked for the possibility of intermediate visualizations. In a previous workshop with K12 educators, educators noted the potential of SPART for students to access as many intermediate visualizations between abstraction (e.g. a map) and reality as necessary to improve their map reading skills. This aligns with the spontaneous suggestion of our interviewee wishing for a gradient map and group 3 (SPART condition) exploiting the feature.

10.6.4 Learning of Collaboration

Based on some limitations of SPART, such as the strong retraction mechanisms (pulling the tablet back when too far from the mechanism), we see potential for gesture-based collaboration, requiring the joined engagement of multiple users to use a functionality and consequently increase overall participation (activities which physically require all members to participate through positive interdependence), coordination (physical coordination required) and awareness (Morris et al., 2006). Such collaborative activities could be destined to raise explicit student awareness (meta-awareness) on the functioning and

importance of collaborative processes and skills.

10.6.5 SPART: An Interaction Drawing Low Cognitive Load

While cognitive load associated to the tool use seemed low (1.5 attempted gestures on the tablet to move the map on average per group), it still adds to the collaborative cognitive load required for the activity. Students already overwhelmed or missing collaborative skills did not benefit from the introduction of SPART. Groups with collaborative skills and solid knowledge on tectonics seemed to benefit from the use of SPART, while groups lacking organization and collaborative skills could not overcome those shortcomings with SPART. This confirms the general consensus that a tool can enhance collaboration but that it is not as important a condition for successful collaboration as collaborative skills and an open and productive social environment. SPART however is an interaction type. It can be used in conjunction with the majority of existing collaborative functionalities that have been developed for tabletops (task related or to regulate collaborative processes directly), all while providing a large and mobile work space with a convenient way of accessing virtual content (Simon *et al.* 2024a).

10.7 PAC Framework Contribution

In this study, we have used the PAC framework so far as a conceptual foundation from which we have derived indicators for collaboration. As outlined in part I, the intended use cases of the extended PAC framework also include documentation of research design and documentation of research results. Indeed, we can map our study parameters as the **input** of the collaborative process as demonstrated in 10.6.

General information, such as time and place of the study can be documented through the environment block: In our study, students worked in a collocated environment, in a workspace that was both physical and virtual. The tools at hand were SPART in SPART groups, tablets, maps etc. constituting both tangible and virtual tools. Given the mix, in future scenarios it probably would be of interest to distinguish each tool separately. Considering the zoom on tool functionalities in part II, the collaborative functionalities implemented (Tool bridging) can also be detailed. The activity has provided some scaffolding along the problem dimension and a scaffolding entity has been present (the educator intervened when he felt it appropriate). Group were composed by performance and the

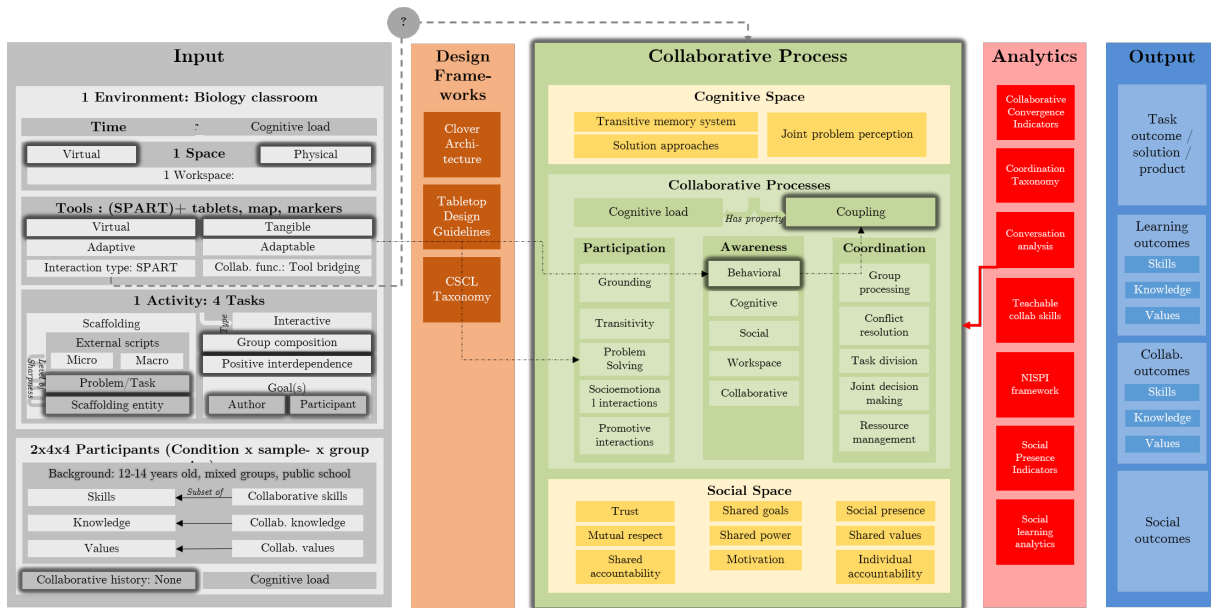


Figure 10.6: The PAC framework in its role as planning and documentation artefact (design frameworks omitted for better readability)

activity featured elements of interdependence. This considerable number of details already shows some limitations of our current framework version. We cannot (yet) detail the type of positive interdependence, nor is there space to detail the properties of group composition. The nature of the study becomes visible through the gray “target” arrow from tool to collaborative process – instead of targeting a particular process and testing for its link to another one, like suggested by Rummels, given the exploratory nature of the study, we simply explored the tool’s role in this study. We did so through the use of conversation analysis (red arrow) and the results hint to the tool assisting behavioral awareness and support collaborative coupling (Figure 10.6). The tool functionality “tool bridging” seems to support the general collaborative process of “problem solving”. These are no definitive results however, a fact represented by dotted arrows.

10.8 Limitations

The study was carried out in **varying conditions**. Group 1 (SPART) and group 5 (control condition) worked in the classroom alongside their classmates, whereas all other groups were placed in empty classrooms to improve voice recording quality for analysis. In addition, groups 3 (SPART) and 7 (a control group) had only 45 minutes compared to 60

minutes for the other groups. Since students knew each other, they had predefined relationships which impacted their group behavior. Camera (wo)men interacted with students and some groups received advice from the teacher. While help from the former occurred on three occasions, the teacher intervened on average twice in every group and session. Furthermore, **available desk space was insufficient** for four students. Tensions may have arisen from the difficulty to work around the tablets. The prototype, physically linking the tablet to the surface, limited possible interactions (string retraction force). In addition, the activity design naturally centered the hypothesis building task around one part of the map, thus favoring interaction with SPART for the person standing at this position. The **activity design** has potential for improvement. The coloring task and classification took too much time and should have probably be compressed into a virtual, automated coloring activity where students could freely pick a color scheme of their choice and autofill the ocean floor layers or keep the original map in order to foster coordination and discussion rather than cooperative coloring.

The **experimental design** would have profited from a within-subject setup to account for a pre-existing social space (e.g. relationships between participants), given that all participants knew each other to some extent and share collaborative history. This is one of the major limitations of this study. **Interviews** with all groups would have provided a more comprehensive view on internal processes than the single interview but could not be conducted due to time constraints. Finally, video material was **analyzed** by a single researcher, who also conducted the subsequent interview, thus exposing him to confirmation bias during the questions. In terms of indicators, the error rate in the use of an interaction does not fully capture cognitive load and stronger indicators (for example usage patterns) would help support this claim better.

10.9 Conclusion

In this comparative exploratory study, we explored the impact of the dynamic horizontal peephole interaction SPART on collaborative learning. The study was conducted in a French middle school with 32 students and a subsequent sequential analysis. We presented our observations and interpretation on the role of SPART for the collaborative processes of awareness, participation and coordination and the social and cognitive space. The results point towards benefits for awareness for high performers and SPART being a support for the cognitive space. SPART seemed to draw low additional cognitive load among

users, was robust and natural to use. It provides a collaborative platform. A number of interesting perspectives for future investigations have been identified: support for mind walks, increased task awareness and learning of collaboration.

STUDY 2: SPART FOR MOBILE COLLABORATIVE LEARNING

In the previous chapter, we described an experiment involving a two-string version of SPART (SPART-ME D V1 I3) to assess its potential for enhancing interaction in collaborative settings. The study revealed promising perspectives for future research, particularly in collaborative coupling, and underscored the role of SPART as an awareness anchor and visual support for group work. However, it did not demonstrate SPART's fitness in a mobile setting. In this chapter, we therefore present a second field study following the successful development of SPART-ME M in September 2023. This study explores SPART-ME in an outdoor environment to evaluate its mobile affordances. We begin by detailing the activity design and the experimental setup, followed by a description of the study parameters and the implementation with SPART. Subsequently, we present our analysis of the recorded video data, before highlighting the results and concluding with a discussion of the study's limitations.

11.1 Context

Students at the age of 10 and 11 in French middle schools typically learn map navigation and plant identification through the use of an identification key. An identification key is a tree-like structured diagram. Each branch has a property of a plant or animal species assigned (form or size of leaves etc.) to help the user identify the correct species situated at the leaves of the tree diagram (figure 11.1). Both skills are well suited for an outside, collaborative and situated learning activity in small groups, since different points of view have to be negotiated and consensus reached, pushing students to reflect on which plant symbol has to be drawn at which position of the map.

11.2 Activity Design

As in the previous experiment, this activity was integrated in the context of the curriculum. The educational goal was to train the skill to **associate a map to physical landmarks** and **identify trees through the use of an identification key**. Additionally, the educator¹ expressed his explicit interest in enforcing collaboration in this intervention.

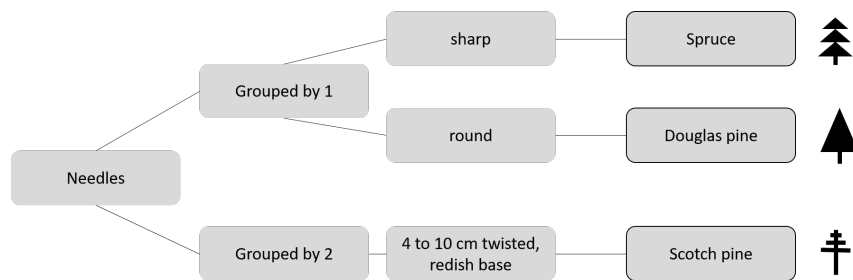


Figure 11.1: The simplified identification key at the disposal of groups

We thus designed an activity in collaboration with the educator, requiring students to identify the position and type of each tree in the schoolyard and mark them on a basic map (figure 11.3, left). Each tree had to be marked with the correct pictogram shown in figure 11.1 on the right. Students had to pick up leaves of the trees to determine their species. However, given the season and the height of the lowest branches, access to leaves was not guaranteed. The control groups could therefore ask the teacher for a leaf, indicating the position on the handed out map. The teacher would then, if the position was correct, give a printed image of the leaf or if the position was incorrect, give a random image to the group. Appendix E presents the assignments (in french) and the questionnaire students had to fill out.

SPART groups in turn were given tokens, one of which in the shape of a magnifying glass. When the token was put on the SPART-ME M prototype, the overlay would react to touch input and display the same images of a leaf as in the stack of printed images that the teacher had at his disposal (figure 11.2). If students touched a location without a tree on the smartphone, a random image was displayed. Students furthermore had versions of a satellite overlay (figure 11.3 center) for a more detailed map and a version of the base map where the areas with trees were highlighted in green (figure 11.3 right).

1. We express our gratitude to Guy Théard for designing the activity with us and his students for testing the prototype.

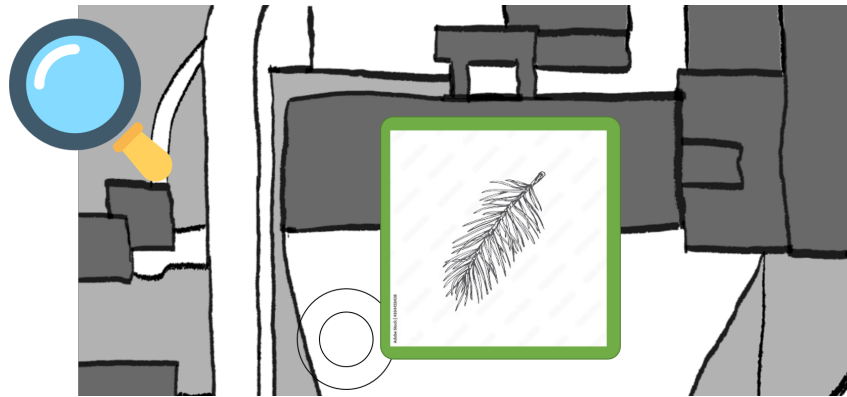


Figure 11.2: Magnifying glass Interface: Users can touch the screen and a leaf is revealed for the given position

Those two overlays in SPART could be accessed through two tokens in the shape of a bird and a tree. Each student in a group was assigned one of these tokens, effectively implementing positive **resource interdependence**. A. Wise *et al.* (2021) demonstrated such use of tangibles as an effective way to weave **positive interdependence** into socio-technological systems by assigning group members personalized tokens enabling different actions in the virtual space. Without a large tabletop to detect such tokens, we designed an NFC shield for SPART-ME M (figure 11.4 left). SPART group members could place their token on the top of the prototype to access the aforementioned functionalities, constituting an additional entry point to the virtual space. Once students had identified position and



Figure 11.3: Different Map Views in the activity that could be accessed with NFC tokens. Left: printed map view, middle: satellite image, right: zones with trees

species, the instruction was given to mark position and species with the symbol of the tree (figure 11.1) on the base map. A score system rewarding each correctly identified tree on a map implemented “common outside enemy” interdependence (inter-group competition). Groups attributed the scores themselves after the experiment back in the classroom, where the teacher displayed the correct species and position on a projected version of the base

map. Each control group had a pencil, a clipboard and A3 printed versions of the three maps (basemap, satellite image and map with highlighted green zones) as well as the activity explanation printed on A4 paper. Each SPART group had at their disposal one version of a SPART-ME M prototype with an attached base map, three tangible tokens to access the two alternative map overlays (and the “virtual leaves”), a pencil and the activity explanation printed on A4 paper.

11.3 Indicators and Conceptual Underpinnings

As in the previous experiment, we relied on the three dimensions of the PAC-framework (Participation, Awareness and Coordination) for the conceptual stance of collaboration. In this experiment, we used an analytical framework of Maquil *et al.* (2024) for more detailed indicators of **coordination**. This framework provides indicators for collaborative coordinative mechanisms (Coordination of information and actions) and also includes a general indicator for collaboration. The latter relies on the notion of collaboration styles, established by Maquil *et al.* (2021). It indicates how many people are working together at which moment of the activity. In our case, the indicator has the factors 3 (all work together), 2+1 (two working together, another one focused on an individual task, 2+0.5 (2 working together, one active listener), 2+0 (2 working together, the other group member missing focus), 1+1+1 (individual, active engagement) and variations of 1+1+0.5 or 1+0.5+0.5 or 0. These indicators are particularly interesting, since they were developed in the context of interactive tabletops with tangible tokens.

We measured **participation** through the number of individual verbal contributions as well as gestures and tool interactions. The importance of an equilibrium of participation is generally seen as a prerequisite for collaboration (Paharaj 2022).

Negative **awareness** indicators included confusion about the group’s strategy or missing awareness of the actions of other group members, resulting in questions like “what is she/he doing?” etc. Positive awareness indicators were associated to successful action sequences without oral explications (behavioral awareness). We also were interested whether students had awareness of the sharing of resources, such as the prototype and asked this question (“I think everybody in the group has had the chance to use the tool” – yes / no) in the post-survey. Since the focus of the study was to investigate the role of SPART for collaboration and its usability, we further asked whether users found the tool helpful (“The tool helped me to achieve the objective of this lesson:” with possible scores from

1-5), what the tool had helped with (“I think the tool helps to better” – open question), and for usability, if the tool was hard to understand (“I quickly understood how the tool could help me”- score 1-5).

11.4 Setting and Procedure

The study was conducted in November 2023 in the school yard of a nearby middle school in two outdoor sessions of 20 minutes. Data was gathered from recorded video and a survey which students filled out directly after the activity. Students were put in groups of three. In each session, two groups used SPART and all other groups used paper-based materials (two of which were filmed as control groups). The SPART groups were given the SPART-



Figure 11.4: SPART-ME M with an NFC shield and the bird NFC token, unlocking a satellite image view on the connected smartphone

Me M prototype (four groups in total) attached to a Samsung S21 Ultra smartphone with a screen ratio of 20:9 and a screen length and width of 14.4 x 6.5 cm. To render the A3 maps portable, we designed 3D printable hinges that allowed to fold the map attached to a rigid cardboard support. For quick assembly and disassembly of SPART to any rigid support, we designed a press fastener mechanism that can be added to SPART and allows to maintain SPART in one position through two holes in the support, all while allowing



Figure 11.5: SPART and control groups during the activity. Left: A SPART group. Right: Control group

non-destructive removal (previous versions of SPART were glued to the support). The control groups had the same information as paper-based material on a clipboard.

The study was carried out on a convenience sample of 24 students, aged 10 to 11. Group composition was orchestrated by the teacher who selected students by their past task performance. Two groups were composed of three girls, while one contained one girl and two boys and the last group was composed of two girls and one boy. The experiment took place in the schoolyard - a rectangular, fenced area of ca. 70 x 30 meters, with two triangular grass areas with a total surface of 15 x 30 m containing a total of eight trees of different specimen.

Each session started with a recall of the previous lesson, an introduction to the importance of working together and the presentation of the activity in the classroom. Students were then introduced to the items they received (prepared on their desk) before getting together into groups and entering the school yard. The experiment was recorded on video by one person designated to follow each group around with a video camera. After twenty minutes, students went back to the classroom, determined the score they had achieved in the activity (points were attributed for correct position and the correct species) and filled out a survey consisting of a system usability scale and questions about their perception of collaboration, whether the group had already worked together, if the tool was comprehensible, helpful and what its role was in assisting the group.

11.5 Results

Based on the limits of the previous experiment, we hired a specialist to code the video material. We provided the above indicators with examples and asked for a complete transcription of the group’s discussions, detailing who spoke at what moment and the gestures of participants.

11.5.1 Participation

We counted 492 oral interventions over all four SPART groups against 446 oral interventions in Control groups. We identified 127 gestures in SPART and 145 in the control groups. We used the Gini coefficient to compare whether the oral participation between group members was well balanced. The Gini coefficient is used in economics to investigate income disparity. More generally, it measures the level of inequality of a variable for a

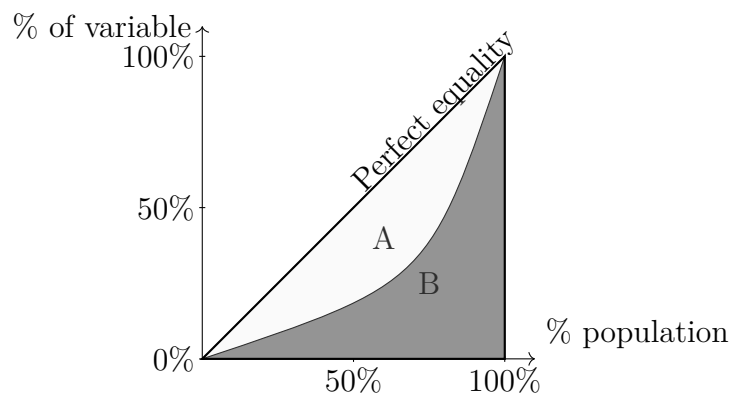


Figure 11.6: Implementation of the Gini coefficient

given population (Dorfman 1979). The implementation of the coefficient in this study is based on the difference on the area under the Lorentz curve B (the actual running total of the variable) and perfect equilibrium, a straight line inclosing area A (see figure 11.6). The higher the coefficient, the higher the inequality (difference between area A and B). Figure 11.7 reports the Gini coefficients for each group.

Overall, a Gini coefficient of 0,20 or lower is considered a relatively equally distributed variable (in economics – there are no reference values for collaborative settings). Under this angle, both SPART and the control groups have a balanced participation. While SPART groups are more balanced on average, a significant difference in coefficients could not be detected in a Mann-Whitney U test (p-value of 0.34). There was also no significant

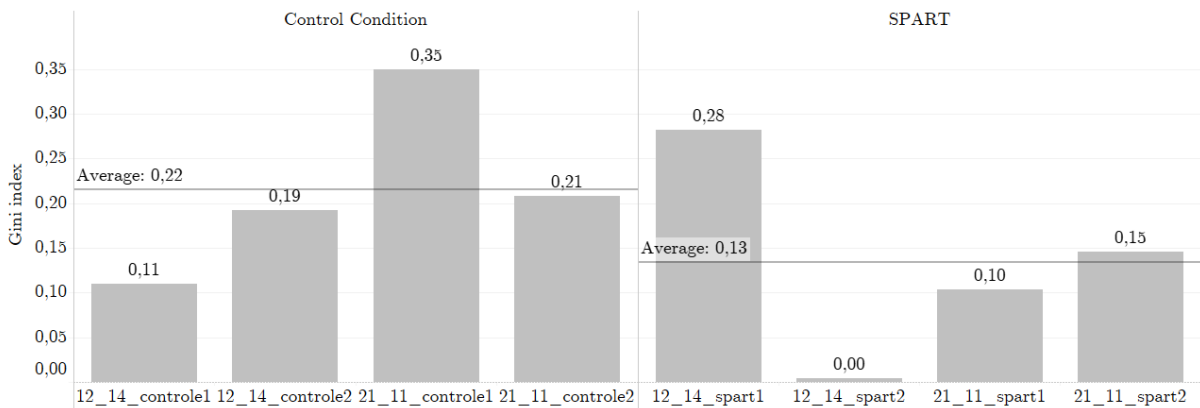


Figure 11.7: Gini Index per group

difference between the number of interventions of girls and boys among SPART or Control groups. Figure 11.8 compares the number of gestures and the number of oral interventions per group. For each group, the number of contributions is detailed per person and gender. Each participant’s contributions are labeled by an identifier composed of the condition (S for SPART or C for the control condition), the group number, gender (B or G for Girl or Boy) and a number for each participant per gender. Numbers do not represent an order of any kind. There is no clear distinction between SPART and Control groups. A slight, albeit statistically insignificant inverse tendency (exempt SPART group 12_24_2) seems to appear between gestures and discourse: More discourse seems to be accompanied by less gestures.

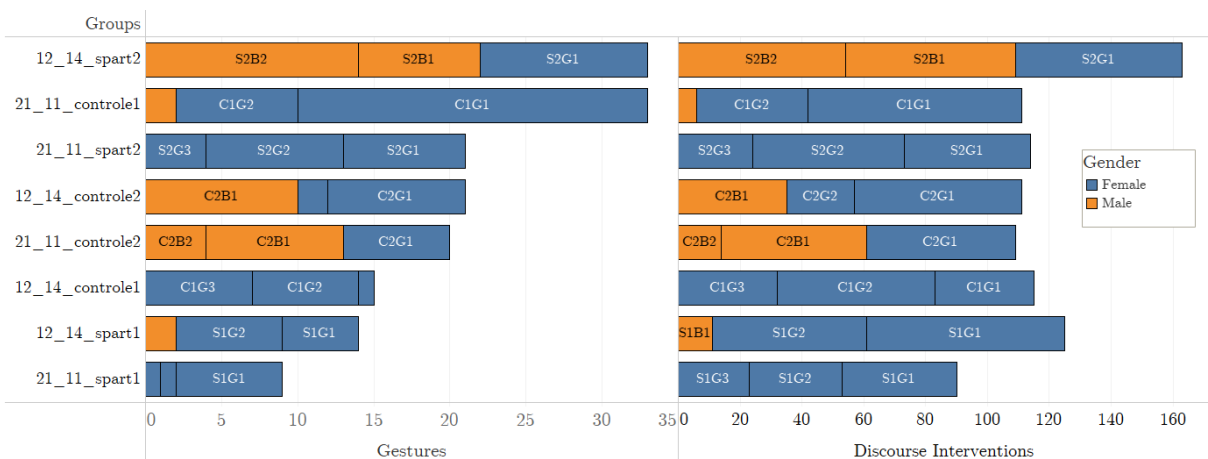


Figure 11.8: Discourse and Gestures by group and gender (color)

As to the nature of these gestures, there exists a difference in ranking, as illustrates

figure 11.9. While both, SPART and control groups pointed at various occasions, the second most observed gesture in SPART groups is turning their heads whereas the control groups were more concerned with picking up leaves and touching them. This general trend is coherent on the group level (the ranking in figure 11.9 applies to all groups).

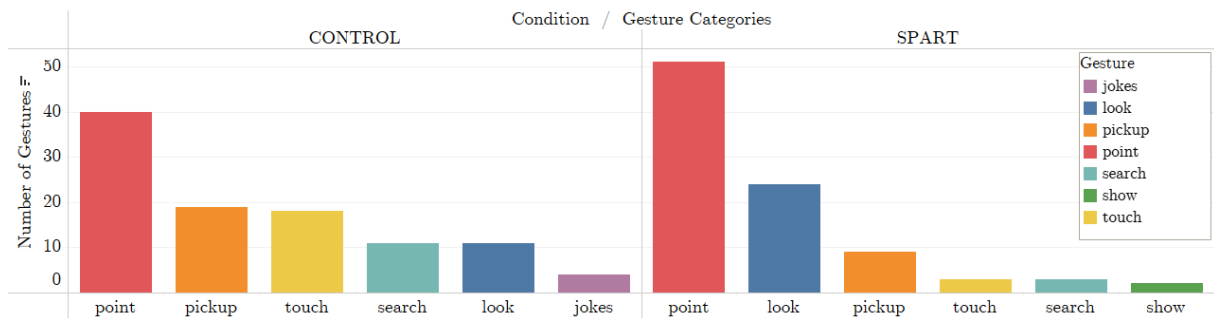


Figure 11.9: Gesture types for SPART and control groups, ranked by descending occurrences

11.5.2 Awareness

Concerning the negative awareness indicator, we identified only 13 occurrences of missing individual behavioral awareness in control groups and 9 for SPART groups (figure 11.10 left). As for missing awareness on what the group was doing, we observed 15 occurrences for the control groups compared to 13 for SPART. SPART groups seemed to have slightly less awareness issues overall. Concerning occurrences of behavioral aware-

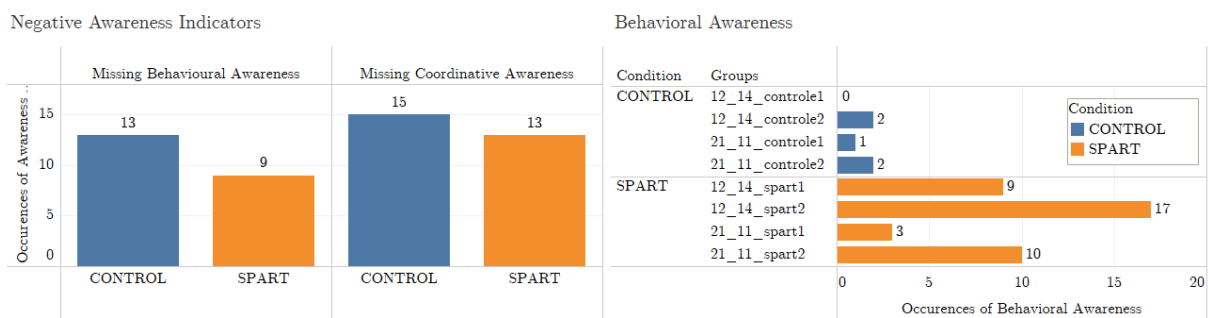


Figure 11.10: Awareness indicators for SPART (orange) and control (blue) groups

ness, SPART groups had more instances of behavioral awareness (for example in the use of tokens and moving the phone interchangeably without oral communication).

11.5.3 Coordination

The framework of Maquil *et al.* (2024) distinguishes between coordination of actions and the coordination of information. The indicators for the former cluster verbal interactions into shadowing, orders, making plans, planning and procedural questions. Coordination of information consists of interpretation of the situation, agree- and disagreements and information requests. Figure 11.11 shows the coordinative action categories in the control condition and SPART groups. SPART accounts for more orders, planning, interpretation and information requests, although the differences are not significant. The surplus in

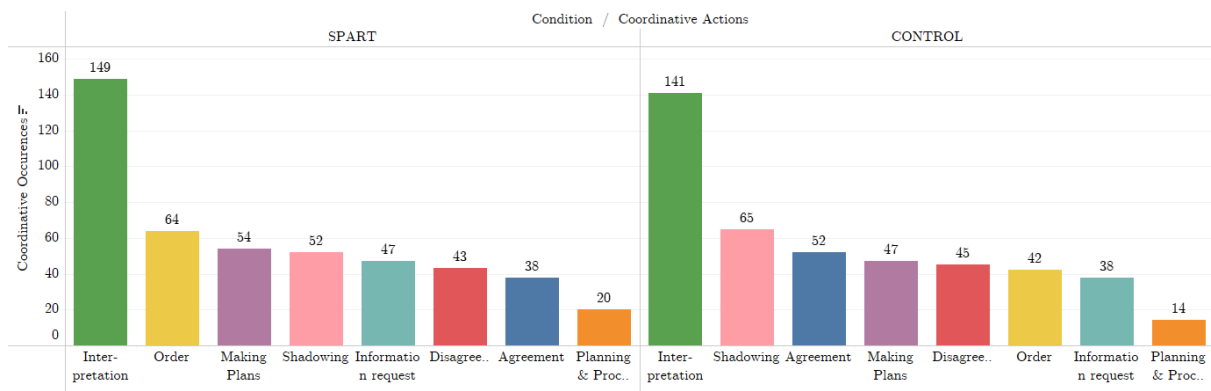


Figure 11.11: Coordinative Actions, SPART vs Control groups.

orders given is coherent within single SPART groups and on the individual level (rank two or three among coordinative actions in 3 out of 4 SPART groups, whereas shadowing in control groups consistently ranks higher than orders, always after interpretation). Finally, we investigated the configurations of collaborative styles. Figure 11.12 shows the total occurrences for both SPART and control groups. SPART groups score significantly (0.013 p-Value in a Mann-Whitney test) higher in the 3, 2+1 and 2+0.5 configuration, whereas the control groups display more of a dyad behavior with one person unfocused.

11.5.4 Tool usage and usability

Among the gestures, we filtered for gestures linked to the use of SPART. This allowed us to analyze how SPART was used in the experiment. Figure 11.13 shows the three categories “move phone”, “token” and “touch” on a group and individual level. SPART was predominantly used in its main function, that is, the map exploration and augmentation, followed by the token use and finally, the use of touch to “pickup” a virtual leaf.

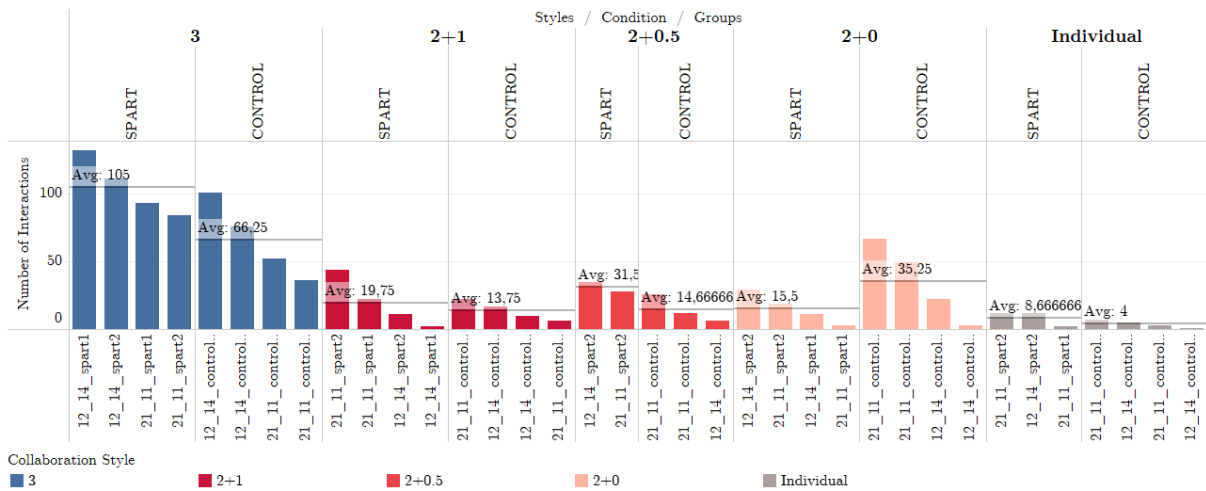


Figure 11.12: Collaboration configurations in SPART and control groups: 3: All 3 group members work together, +0.5: one active listener, +0 disengaged group member

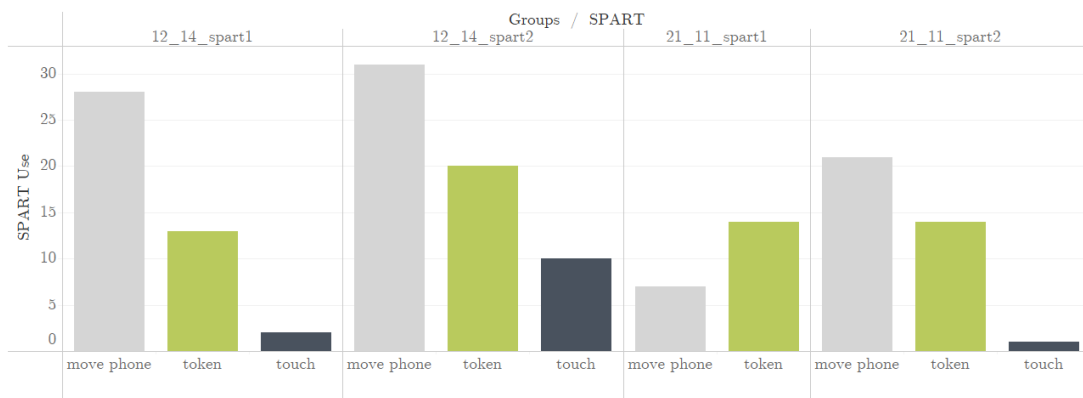


Figure 11.13: SPART related gestures on the group level

The group (12_14_2) with the most touch interactions has 0 pickup gestures, followed by a single pickup for 12_14_1 which has the second highest score of touch gestures among the four groups. Group 21_11_1 without any touch gesture has the highest number of pickup gestures (this was due to the fact that the magnifying glass token had a technical issue for this group and was unavailable – this group was told to ask the educator for printed images just like the control groups).

In the survey, participants were asked whether they thought that everybody had the possibility to use the tool. All participants agreed, which is coherent with our video analysis. The survey also resulted in a system usability score of 68.75 out of 100 which is attributed to “good systems” on the lower end of the range (“OK” ending at 68 points). The unified negative answer to the question “The usage of the tool has made the lesson

harder” is an indicator to the little extra cognitive load induced by SPART. Similarly, students saw the tool as assistance to navigating the map and to understand where elements on the map were located (answers to the question “I think the tool helps to. . .”). Task wise, all groups located the trees at the correct position. Finally, we investigated the

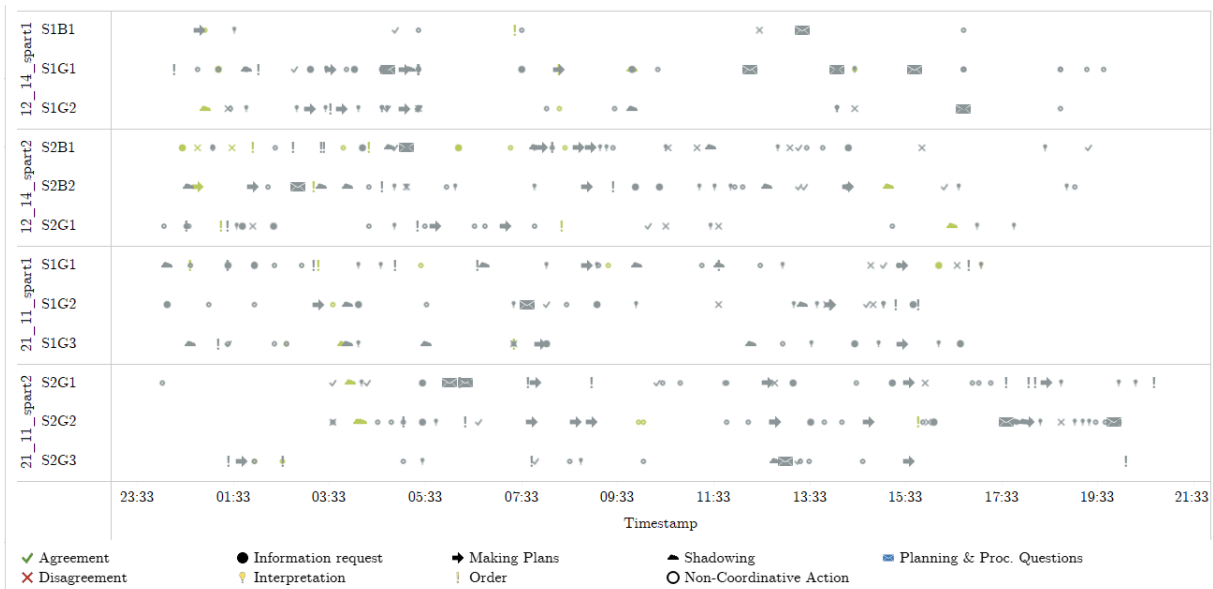


Figure 11.14: Sequence of coordinative actions. In green: tool concurrent actions, in grey: actions without tool use

higher number of orders given in the SPART condition (compared to the control groups). Orders are indicators for hierarchy, generally an unfavorable condition for collaboration. This is less of an issue if the order is the result of a planning phase or consensus (resembling more a nudge than an actual order). Figure 11.14 shows the different coordinative actions. In green are highlighted the actions that occurred with a tool interaction. Exclamation marks represent orders. As can be seen, the majority of orders is not preceded by a plan, and subsequent conversation analysis would reveal that the orders were indeed given without explanation or consensus. Coincidentally, their occurrences were also mostly linked to the use of a participant’s token.

11.6 Discussion

Groups with SPART-ME M showed significantly more collaborative styled interactions compared to the control group (Mann-Whitney test) . Albeit the occurrence of orders

within SPART groups, SPART groups had more interactions among the whole group. The appearance of orders is an interesting finding which goes to show that the “simple” implementation of positive resource interdependence might still be improvable, especially in young participants, who tend to interact (at least during this experimentation) in a very “direct” fashion, not patiently explaining why the use of the peer’s token would be of interest for example. Still, it seems to be effective to enforce collaboration. This is also an interesting perspective for a future study with SPART prototypes without positive interdependence as control condition and SPART prototypes with positive interdependence in this setting to investigate to which extent collaboration occurs through the interaction or the positive interdependence. There were also more instances of behavioral awareness among SPART groups. This may simply be due to the SPART setup featuring more possible interactions with objects (tokens and phone movement), or due to the fact that members who rejoined the group after an individual phase had strong visual cues of what the other group members were doing (position of the phone and type of token placed on SPART).

In terms of collaborative functionalities, we deployed activity enforcement (part II, chapter 3) in that group members had access to different, activity relevant parts of the software through their tokens. The implementation of such features however requires caution with respect to the pedagogical goals, since it appears that the presence of the magnifying glass token led to less interaction with the environment – the key feature of situated learning.

The survey results confirm the interest of SPART as an assistance to bridge abstract plans and reality (with intermediary visualizations such as the satellite image (of which groups made good use). A perspective on this aspect could be a more systematic study, providing for example more intermediate layers, both with less information than a satellite image and more – for example the use of 3D models (e.g. from google maps) in a dedicated map navigation task. Another approach (and potential replacement for the hourglass functionality) would be to display the position of users on the map – either directly with their relative orientation, or just with indicators (e.g. arrows at the bounds of the display until the smartphone is framing the user’s location without showing it). Users attributed a good System Usability Score to the SPART system, even despite problems like the mobile phone detaching itself from SPART on three occasions, the detaching of one of the hinges in one SPART group and a bug making the magnifying glass unavailable to one of the four SPART groups.

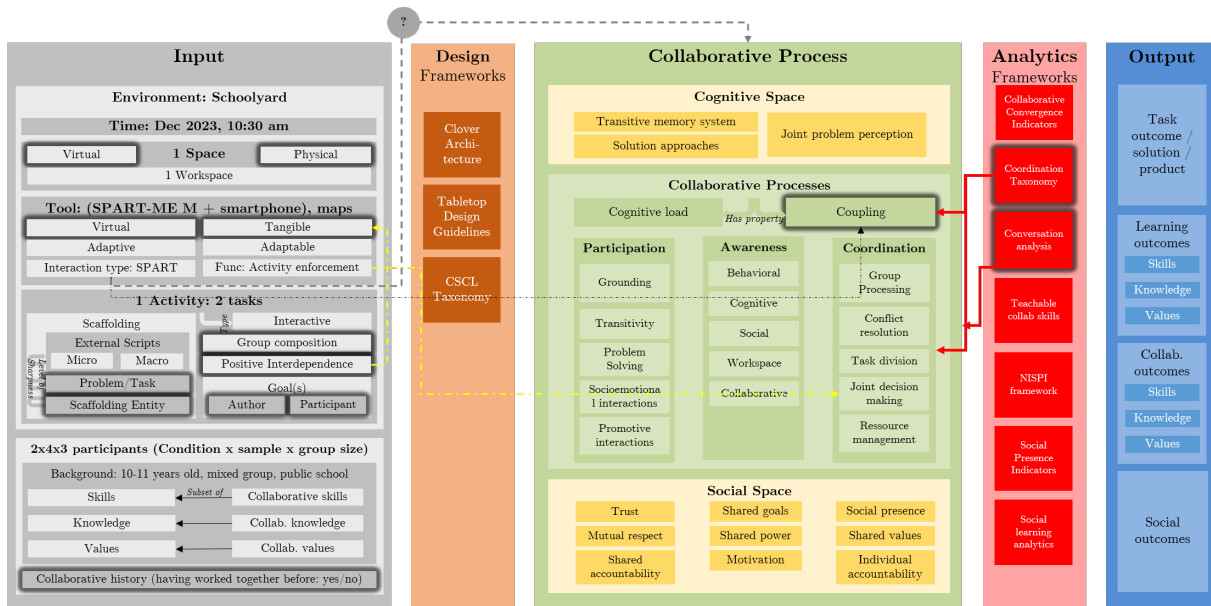


Figure 11.15: The PAC Framework as documentation tool for this field study. In yellow: potential negative relationships.

11.7 PAC Framework Contribution

As in the previous chapter, we have made use of the Core PAC framework for our conceptual grounding. Figure 11.15 shows the extended PAC framework in its role as a documentation tool for this study: As in the previous study, we detailed the tools used, their properties, as well as activity details. Likewise, we were interested in the collaborative process (instead of any collaborative outcome). The study’s results point towards a positive impact for collaborative coupling by the tool, a collaborative process property we assessed through a dedicated framework (Maquil *et al.* 2024) that also allowed to reveal a higher use of the interaction type “order” among SPART groups in the context of the implementation of positive resource interdependence through NFC tokens.

11.8 Limitations

The fact that the participants did not perceive SPART, and its foldable support on with the smartphone was attached, as robust, seemed to modify their behavior: they would carefully walk across the schoolyard instead of running like their peers in the control groups. While SPART performed well (even under rain), improvements, such as a mechanism to hold the smartphone in place while on the move, are necessary for future experiments to

bring the experience closer to the paper-based material in terms of freedom of movement.

Another limitation of this field study was the use of the System Usability Score, containing vocabulary the juveniles weren't sure they understood correctly and required the intervention of the educator and the film crew. The acquired data could also be more complete: for example, through usage logs on the smartphone (where has the smartphone been moved and what are the path the group has taken outside through GPS tracking). Finally, this has been a qualitative study. Even though we could identify significantly more collaboration with SPART, more research is still required to confirm the results and test how this combination of functionalities fares in other, different contexts.

11.9 Conclusion

In this chapter, we have reported the results of a field study with SPART-ME M in a situated learning setting. We have implemented positive interdependence alongside the SPART interaction in this activity intended to train students' navigational skills and ability to identify tree species by their leaves' properties. SPART has proven robust, easy to use and helpful for the pedagogical task of navigation. SPART groups have collaborated more than the control group without SPART, outlining the interest of SPART-Me M for future collaborative activities.

USABILITY TESTS

The science fair “Le Mans Sonore” was a cultural event for the general public around Le Mans, France, to promote the acoustic expertise of its laboratories and industry. In 2024, our team was invited to present SPART-AC, an acoustic version of SPART, co-developed with LAUM acoustics laboratory (presented in chapter 9). A game for the acoustic prototype was designed by an intern financed through a cross-laboratory funding opportunity. This game was presented in the “cabinet of acoustic curiosities” during the science fair, placed at the end of a guided tour through the LAUM laboratory.

Alongside SPART-AC, we also exhibited SPART-ME MV2, a mechanical variant of SPART, on our stand during two days to observe the type of interactions unfamiliar visitors would have with it. We recorded each interaction and collected traces from 67 visitors, which will be described and analyzed in this chapter. Initially, we intended for visitors to fill out a System Usability Scale, which proved impossible due to the fact that our stand was placed at the end of the exhibition, itself at the end of a two hour guided tour (visitors showed signs of exhaustion).

12.1 Activity

Locals were the most expected visitors. We consequently designed a short game consisting of identifying historic buildings on a map of the city of Le Mans. The static support consisted of an aerial map of Le Mans with data from 2024, while the virtual overlay (displayed on the smartphone screen) featured a map of Le Mans in the late 1700s. Users were asked (on-screen instructions) to touch the position they thought a landmark was located at. The game featured six landmarks to discover (churches, fortifications, hospitals etc.). Once the user tabbed on the correct position, an icon of the building appeared in the virtual layer and the name of the next landmark to identify was displayed. Users had previously the possibility to test SPART-AC, thus visitors were already (to some extent) familiar with the SPART interaction. However, as mentioned in the previous part, SPART-AC requires manual intervention after each movement of the tablet to determine its position and adjust the virtual overlay (all while having an accuracy below 2 cm). We

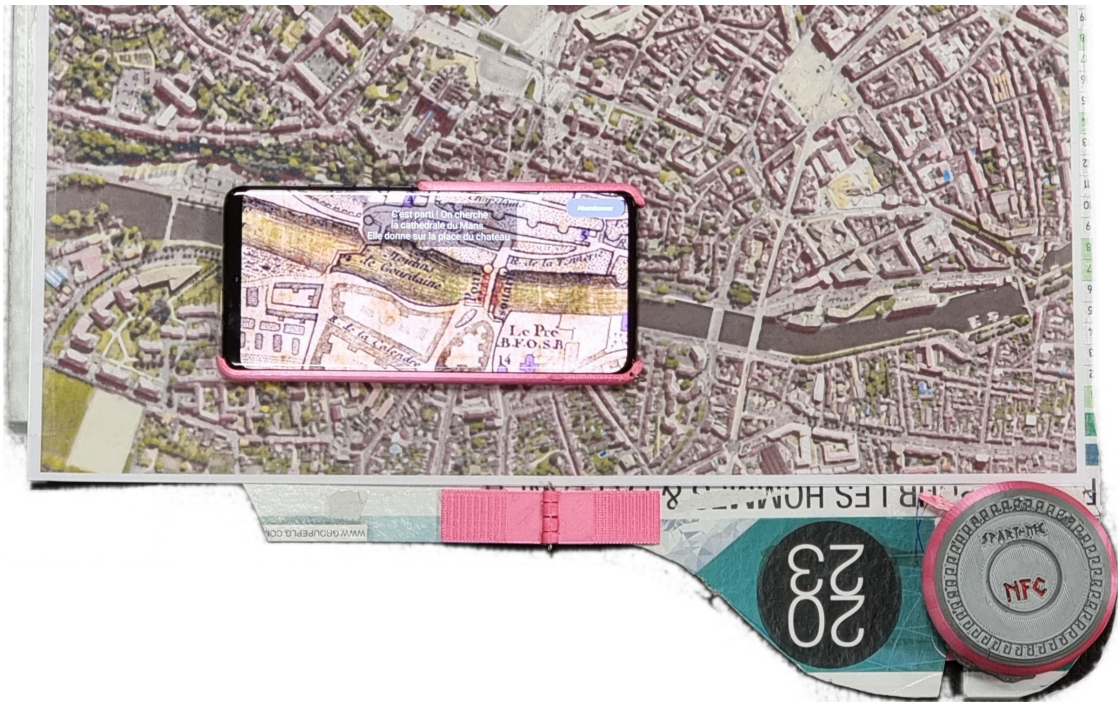


Figure 12.1: SPART-ME M on a map of Le Mans city center and the augmentation of a 18th century map

thus proposed to visitors to try out the SPART-ME M prototype afterwards to showcase what the SPART interaction is supposed to look and feel like. If visitors agreed, they were given an oral explanation of the virtual overlay and the physical map along with the game objective and how to uncover the different landmarks in the virtual layer.

12.2 Setup and Tracking

The device was a smartphone Samsung S21 Ultra with a screen ratio of 20:9 and a screen length and width of 14.4 x 6.5 cm, tracked by a single string mechanic version of SPART (figure 12.1). Software side, a functionality to track player progress (to sequentially display the different landmarks) and tracking of user interactions was implemented. We used a csv file to store the following user actions on the phone:

- start and stop of the application
- start/end/abort of a game
- successful identification of a building
- moving the device

- touching the screen

Every event was recorded with a timestamp and the events “moving” and “touching” were recorded with their respective position on screen or relative to the SPART device. Each visitor or group of visitors that interacted with SPART-ME was assigned a unique ID when a new game was started.

12.3 Results

We excluded any empty session (no touch event or movement recorded) before proceeding to analyze the interactions. We recorded 58 active users of which 31 touched the phone screen and 21 identified at least one landmark. The average interaction duration per session was 3 minutes and 50 seconds, the median interaction time 2 minutes 30 seconds (figure 12.2). Since we were particularly interested whether users would try to use gestures

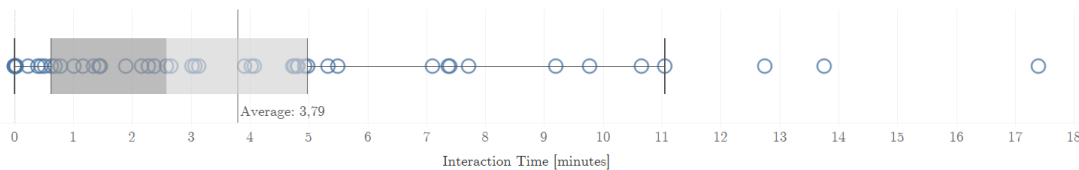


Figure 12.2: Interaction time in minutes

instead of moving the device as an indicator for usability, we clustered the **touchscreen interactions** by distance in order to distinguish the different interactions of a same user. If the next interaction data point was more than 50 pixels away (4 mm) and delayed by 50 ms, it was considered a separate gesture. We identified 180 separate interactions on the touchscreen. Another filter we applied were interactions on the screen located in the rectangular area between (0,0) and (250, 80), since those touch gestures correspond to the Android interface overlay (and correlated with the action of leaving the application). The result can be seen in figure 12.3: Dark orange dots show the start of an interaction. 121 out of 169 interactions have been clustered as simple touches (blue), based on a 50 px (4 mm) threshold between the most distant values. For reference, this is 3 times the default threshold of the Android system. This difference accounts for posture of participants, standing and using their stretched out arm to interact with the smartphone, reducing accuracy (Chourasia *et al.* 2013).

Similarly, we clustered data points of movement actions with SPART. Given that SPART movements started at the end of the previous movement, we clustered by time

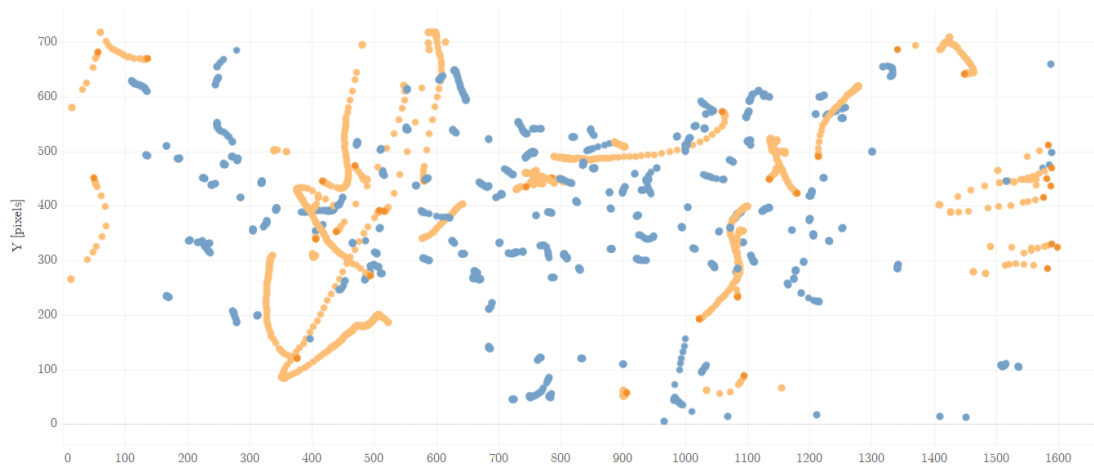


Figure 12.3: All touchscreen interactions. Blue: clustered as single touch, orange: clustered as gesture, dark orange: start of gesture.

difference between data points: An interval of more than 500 ms was considered a new interaction. The SPART prototype itself was configured to an update speed of 100 ms. Consequently, we obtained a total of 3478 movements, with an average of 59 movements per visitor and 50 % of all visitors having more than 31 interactions. The difference

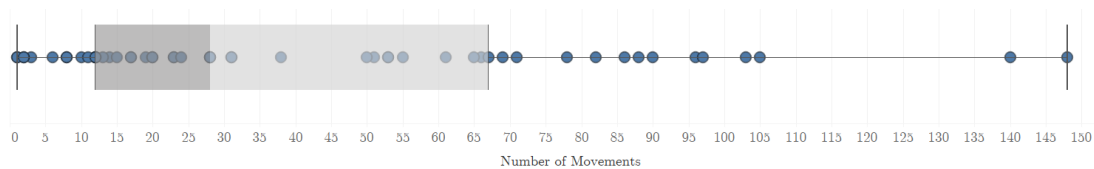


Figure 12.4: Number of movements with SPART per visitor

between **SPART interactions** (moving the phone) and **touch interactions** was notably due to the fact that visitors, especially seniors, did engage with SPART without engaging in the game activity, motivated to explore the virtual layer or discover what the places where their homes are located today looked like in the 18th century (based on observations and interactions with visitors).

We further investigated the use of attempted **swipe** gestures, as a way to determine whether users had trouble using the SPART interaction (and tried to resort to the more familiar static peephole interactions). On average, each user had 1,5 attempted swipe gestures in their interactions. However, the distribution is not homogeneous: Out of 32 recorded swipe gestures, four of the 59 users accounted for half of the gestures. Three of those four users engaged in the game activity. Furthermore, 10 of the 31 swipe gestures

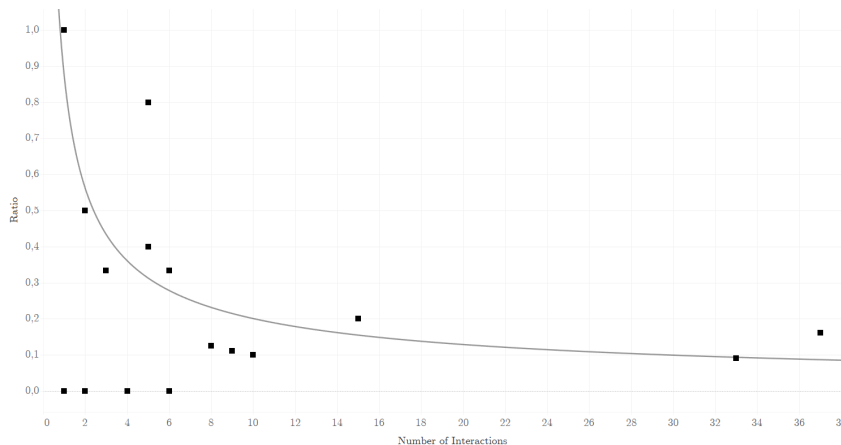


Figure 12.5: Gesture to Touch Ratio vs total interactions: The more interactions, the less errors

coincide with a SPART interaction. Such occurrences point towards an accidental touchscreen interaction while moving the phone during a SPART interaction. We calculated a gesture to touch ratio (how many times users tried to use swipe gestures over the total number of their touchscreen interactions) which we put into relation to the total number of touchscreen interactions. As figure 12.5 shows, the decrease in the “error” rate is exponential. This means that not only do errors decrease with more use of SPART, but instead of doing so gradually, they do so immediately after one or two failed attempts (figure 12.5). These are comparisons on the scale of the occurred touchscreen interactions. Compared to the 3478 total interactions with SPART, the number of attempted interactions ($<0,1\%$) on the touchscreen are negligible.

12.4 Discussion

We interpret these results as an indicator for a good learnability of the SPART system - in that temporarily unlearning touch gestures in favor of a dynamic peephole interaction does not require high cognitive load (for the public of this fair), even after two hours of a guided visit, with a variety of cognitively demanding explanations on scientific experiments and acoustic prototypes. The nature of results lines up with the two previous experiments.

SUMMARY ON CONDUCTED STUDIES

In this part of the dissertation, we presented two field studies carried out in a middle school and a usability test led during a science fair, deploying the SPART variants SPART-ME D and SPART-ME M.

The two exploratory field studies were conducted with a young public, whereas the population during the science fair had a broader age range. We analyzed our video data of the two field studies through the point of view of the PAC framework presented in part I. Analysis was carried out in the first field study through conversation analysis by ourselves, a limitation we addressed in the second field study, where a professional coder was commissioned. For this second study, we made use of the recent analytics framework by Maquil *et al.* (2024) which fits the structure of the extended PAC framework, its integration thus another perspective for the latter. SPART-groups showed a higher degree of overall collaboration and a slightly higher level of orders in their communication.

For the analysis of the usability test during the science fair, we recorded interactions with the smartphone and clustered gestures as a negative indicator for the ease of use (the SPART interaction being a dynamic peephole interaction requiring the phone to be moved as opposed to the classic screen gestures). While isolated gestures occurred in the beginning of some of the sessions, the error rate immediately dropped over the consequent interactions in all three experiments, which we interpret as an indicator for fulfilling **interaction realism**. This was one of the hypothesized interaction requirements identified in part III, chapter 7. Throughout the studies, the SPART interaction, implemented through its mechanic prototypes, proved easy to use, in a classroom environment, fair stand and outside under light rain. The prototypes themselves displayed robustness in all conditions, albeit some minor design flaws that still have to be addressed.

Both studies strengthen the hypothesis of SPART as a collaborative support by augmenting static surfaces. The role of SPART as a **visual argumentation support** has been observed in both studies. SPART-ME M has proven reliable and practical in a mobile setting. It remains to be seen if SPART also can be an appropriate support for other activities than information retrieval tasks, for example brainstorming or the creation of a virtual artefact requiring more complex interactions than the few buttons we implemented

in the three applications. More generally, the results align with literature for the interest of dynamic peephole interactions in navigational tasks on small screens (such as X. Li and C.-H. Chen (2020)) and extend these findings through the collaborative aspect of the experimentations.

All three experiments have yielded a number of applications and perspectives for further studies. Most importantly, more collaborative experiments are required to confirm the results of our preliminary studies. Thus, the most important perspective of the experiments is to ensure there are more experiments conducted in collaborative settings and support motivated researchers and practitioners in their intention to produce and share data from these experiments. As stated in the previous part, the SPART-ME prototype family is designed to be built and repaired with minimal skills and investment. We thus intend to focus in the next step on providing the means to track data from SPART and the conceptual and analytic foundations for easy analysis and sharability. SPART is an interesting interaction for collaborative settings and to further test its abilities and limits, a collaboration is, what we believe, required and is the next endeavor on which we intend to embark on.

PART V

Conclusion and Perspectives

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RESEARCH QUESTIONS

The work presented in this thesis is situated within the domain of TEL (Technology Enhanced Learning) and, more precisely, CSCL (Computer Supported Collaborative Learning). The identified problem of supporting mediated collaborative learning, in a mobile setup, through the means of technology, has led us to three research questions:

- RQ1: Does an augmented reality interaction consisting of a mobile device, being placed and moved across a static surface, constitute an improved collaborative learning support? If this is the case, how does it influence collaboration?
- RQ2: Does a comprehensive list of collaborative tool features exist? What is their impact on collaboration? How do different combinations of features affect collaboration?
- RQ3: Given the multi-domain nature of CSCL, does a common vision of it exist? If not, can we establish common ground from existing literature?

These three questions are intertwined: RQ1 led us to formulate RQ2 and the answer to RQ3 is required for RQ2 (yellow arrows in figure 13.1 highlight these dependencies). In order to design an activity and collaborative support, we had to establish what functionalities could be implemented to support collaboration (RQ2). In order to identify such functionality and evaluate its impact on collaboration, in turn, a joint vision of collaboration on the conceptual level was required beforehand (RQ3). This dependency defined the order of the four previous parts of this dissertation, and consequently, we present the following sections and chapters on perspectives and limits in this descending dependency order (RQ3 to RQ1). We first draw up a summary of what has been accomplished and how it has been accomplished. We then dedicate to each contribution a chapter to highlight its limits and perspectives.

SYNTHESIS

The following sections each discuss the contributions to our research questions and recapitulate the deployed methods and the publications these contributions have resulted in.

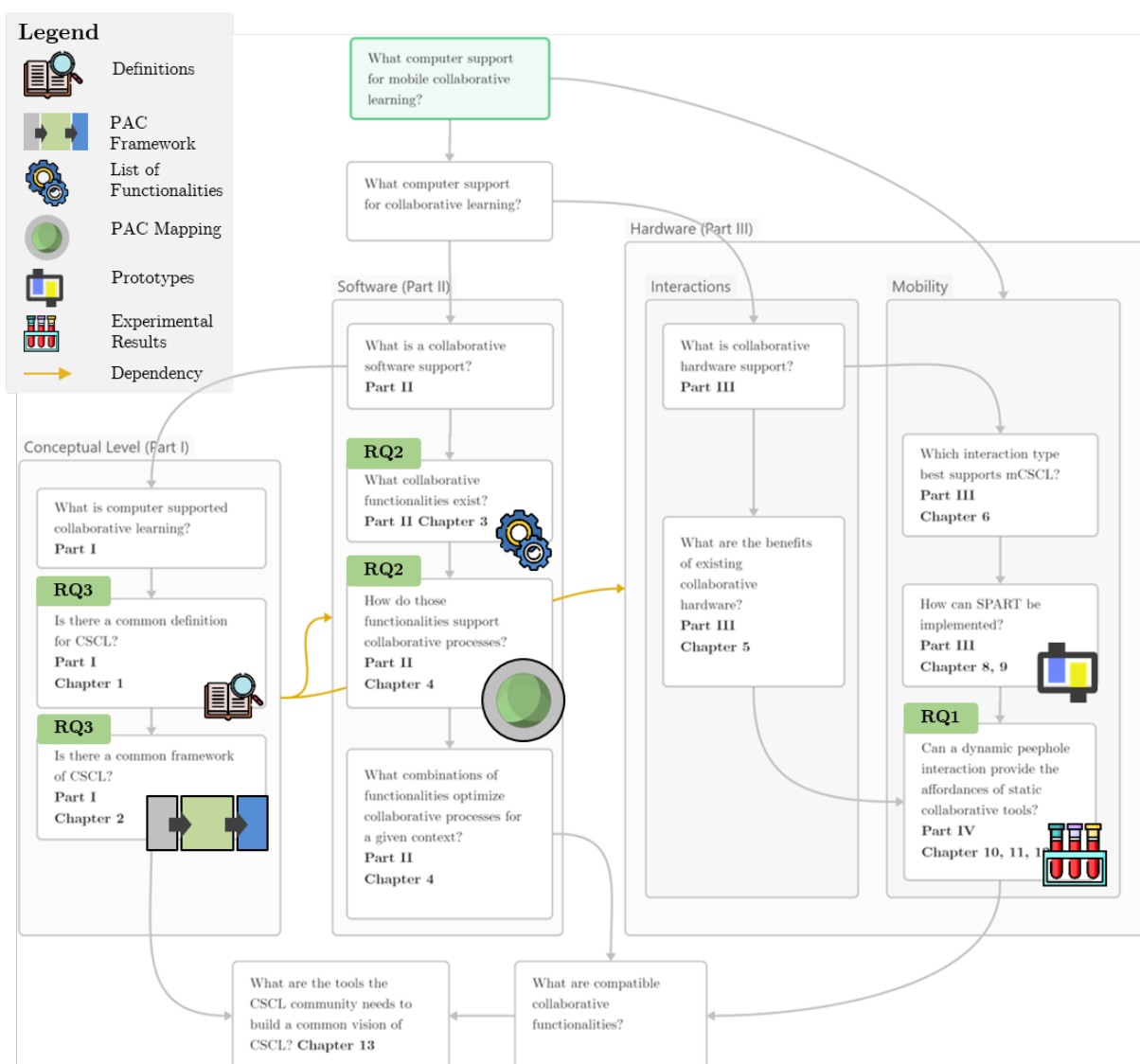


Figure 13.1: Research questions (in green) and intermediary questions with contributions

13.1 A Joint Vision of CSCL (RQ3)

In part 1 of this dissertation, we established **definitions for collaboration, learning, collaborative learning, computer support and CSCL**. In chapter 2 we established the **PAC Framework**. This conceptual work had an impact on multiple levels (as are to illustrate the yellow arrows in figure 13.1).

Firstly, it allowed us to construct a **systematic representation of collaboration** by combining the many perspectives that exist in the field. The **literature review on collaboration definitions** helped us understand the diversity of perspectives and the linguistic uncertainty surrounding concepts like cooperation, collaboration, cooperative learning and collaborative learning, but also highlights the common core on which we could build our framework. The Core PAC Framework was published at the 2022 ECTEL conference (Simon *et al.* 2022b) and at *Les rencontres des jeunes chercheurs 2022* (Simon 2022). The **Core PAC Framework** was obtained through a comparison of 3 frameworks for the collaborative process. Through the analysis and integration of four complementary frameworks, we detailed the input and output dimension of the framework, the latter of which allows to distinguish different applications of collaboration such as CSCW, Collaborative Learning and team building. The **extended PAC Framework** is based on the Core PAC Framework and a systematic literature review, detailing existing dimensions, linking elements and integrating design and analytic frameworks. The PAC Framework has been applied in part II and IV as the conceptual groundwork for a meta-analysis and our experiments. Establishing a vision from common ground has allowed the comparison of different studies for the work on collaborative functionalities. It later supported the design of our experiments and presents a basis for common ground on the community level. The potential of the extended version as a tool for documenting experiment setups and results has been illustrated in the two conducted field studies in part 4. As a community artefact, the definition and framework were published and presented on the 2024 ISLS/CSCL conference (Simon *et al.* 2024c).

13.2 Collaborative Functionalities Mapping (RQ2)

While RQ1 focuses on interactive (and thus mostly hardware-related) affordances of collaborative and mobile tools, computer support, also consists of software. The equivalent to the question “What is collaborative hardware support?” we needed to ask, in order to

design activities and software for our studies, was thus: “What is collaborative software support?”. As there seemingly was no general answer to this question in literature (such as a list of software features that had been found to support collaboration and to what extent) we compiled such a list ourselves through a literature review. The literature review of 49 studies, in which we analyzed and extracted the features from the different CSCL studies, resulted in **a list of 20 distinct and recurrent functionalities**. Next, we proceeded to evaluate the impact on the different aspects of collaboration of these functionalities on the corpus of studies. We studied individual impact along the PAC Framework dimensions, resulting in the **PAC Mapping**. The result can be considered a design guide, the first of its kind at this level of detail (to the best of our knowledge) for collaborative software design. This mapping was published and presented at the 2023 ISLS/CSCL conference (Simon *et al.* 2023).

13.3 SPART as Collaboration Support (RQ3)

From the domains of situated and collaborative learning in the context of the project Situlearn, originated the need for a tool both mobile and collaborative. To this end, we reviewed existing approaches in literature. Collaborative hardware and mobile approaches all have in common **a shared workspace** to support collaboration. Consequently, we researched interaction types that could ally a shared workspace with mobility through a set of properties for low cognitive load. We identified **SPART, a novel horizontal dynamic peephole interaction**. To explore the question whether SPART could support mobile collaborative learning (RQ1), we firstly established a set of requirements that a prototype implementing such an interaction has to fulfill in the educational mobile context. We then conducted a systematic literature review on three techniques applied to 21 physical phenomena to identify 37 technologies which we evaluated against these requirements. As a result, we developed a total of 18 prototype variants of which 3 fulfilled the requirements established prior to the literature review. The successful development of two mechanical variants (SPART-ME M and SPART-ME D) enabled the design of two field studies and a usability test during a science fair. To this end, we designed two collaborative activities and specialized software. The field studies shed light on the potential of SPART for collaborative coupling and behavioral awareness. The usability test during a science fair confirmed the ease of the interaction, already highlighted during the two precedent studies.

The long paper of the prototype SPART-ME D at the Mobile Learning conference 2024 won the best paper award (Simon *et al.* 2024d) and was accepted at the MOMM conference 2023. The prototype SPART-ME M was presented at IHM 2024 (Simon *et al.* 2024b), as well as at Laval Virtual 2024. The results of the first experiment are the subject of a publication at CSEDU 2024 (Simon *et al.* 2024a) and at Les rencontres des jeunes chercheurs 2024 (Simon 2024). The systematic state of the art is, at the time of writing, in the process of submission to the journal *Foundations and Trends in Human Computer Interaction*.

LIMITS

14.1 Definitions

In part I of this dissertation, we established four definitions of CSCL, Computer Support, Collaborative Learning, Learning and Collaboration, as well as two variants of the PAC Framework of collaboration. The definition on collaboration has most notably allowed an extended definition for CSCL as a domain. Language, however, is a dynamic system, and definitions are subject to change, especially in a context as dynamic as CSCL. Thus, it does not suffice, from our point of view, to punctually define a concept or establish a framework. To create the definition of collaboration, we have used a technique called **defining vocabulary** relying on the frequency of recurring elements in other definitions. These definitions have been established over the past 30 years. It could be argued, that, to reflect current use of the defined concepts, a restriction should be made to recent definitions. Furthermore, the authors of these definitions come from different domains and it seems natural that these definitions diverge (although it could be noticed that the concepts that make up our definition, have stabilized over time).

14.2 Frameworks

The extended PAC Framework is an artefact we created by analyzing existing frameworks. Over the conducted literature review, the number of elements of the framework grew to a point where the visualization could not hold all the details surrounding research on collaboration. The necessity to split up the different relationship visualizations is just one example of this aspect; the impossibility to further detail different elements, such as the list of promotive interactions by D. W. Johnson and R. T. Johnson (2009), the script framework by G. Fischer (2013) or the transactive framework (Weinberger *et al.* 2005) is another. Moreover, we highlighted the importance of the activity design without having elaborated in detail the variety of collaborative activities in existence today. After several literature reviews conducted in the domain, we feel that there is a necessity for a framework of collaborative activities and their role on the different PAC processes to

further differentiate the relationships of the elements depending on activity context.

14.3 PAC Mapping

In part II of this dissertation, we identified 20 functionalities with potentially positive impacts on collaboration. We then attempted to map these functionalities on three dimensions of collaboration, resulting in the **PAC Mapping**. In this initial approach, we intentionally ignored the educational activity that the students were collaborating on, due to the variety in our initial dataset. This is a major limitation for the applicability of the diagram as design framework, since the activity is the defining aspect of collaborative learning. Another aspect is the limited number of functionalities. Tools of social comparison for individual accountability, even outside the realm of CSCL, have shown promising results (see for example Broisin *et al.* (2017)) and have the merit to be investigated for their potential in collaborative settings.

14.4 Prototypes

The conducted **systematic review of technologies** for the SPART interaction relies on the combination of physical phenomena and localization techniques. The former is a domain beyond the comfort zone of the author. Although a physics professor validated the proposed classification, it might be possible that physical phenomena have been missed. At the technology level, although the systematic approach has been invaluable to guide the search of product and existing prototypes, the use of search engines cannot guarantee a complete picture of the existent. The mechanical prototype SPART-ME M has scored 10.5 out of 12 possible points in our evaluation of prototypes and technologies. However, attaching a string to a phone or tablet whenever one wishes to use the prototype, and attaching the prototype to a rigid support restricts practicability. Currently, the initial calibration phase is long and requires programming code modification, further reducing accessibility.

14.5 Studies

The limits of the conducted studies have been stated in their respective chapters: Both studies have small sample sizes and are composed exclusively of students of the same age.

The classroom study had its activity enriched with clues for students after the first groups failed to finish the activity. The data was coded by the same person who analyzed the data and there was only one person interviewed after the study. The second study in the school yard featured a system usability score which the students had trouble understanding and one of the tokens did not function during the activity due to a software bug.

PERSPECTIVES

It is obvious that our work has to be continued to further elaborate the research questions. This is the purpose of this chapter: If our work is a step to a better understanding of collaboration and a partial answer to our main research problematic (how to support situated collaborative learning), then the following sections might be the most interesting contribution: A focus on what is required to answer those questions, based on our experience on the topic. The following sections will thus detail perspectives to each of the previous parts, beginning with a conceptual stance in section one, an analysis on the functionality part of collaborative tools in section two, while section three will present the perspectives on SPART, the prototype and its applications and potential adoption. Section 4 will conclude on long term perspectives based on our conducted field studies and in section 5 we discuss to what extent our work can inform the design of its contending project, SituLearn.

15.1 Definition and Framework Refinement

The following subsections highlight how definitions and conceptual visions may evolve. We first discuss future work on definitions, before outlining perspectives for the PAC framework, then arguing for appropriate tools and processes to handle the maintenance of a dynamic version of the PAC as collaborative artefact. Finally, we highlight opportunities for research collaborations, describe the use of the framework in a use case and highlight its possible role as an entry point to the CSCL community for newcomers (such as PhD students).

Enhancing Definition Quality

Given the limits of our current definition, we are, at the time of writing, conducting a survey among the CSCL community, to define the concepts of Learning, Collaboration, Collaborative Learning and CSCL. The objective is to restrict the domain scope and obtain a recent image of the conceptual perceptions in CSCL. ISLS 2025 being the targeted conference for this submission, we intend to raise awareness among the community for the

issue through participation in the survey before and in exchanges around the topic during the conference. The work is a collaboration with researchers at the university of Zagreb, Croatia, Danube university, Austria, Pittsburgh university and Rochester university, US.

Proposing a PAC Ontology

As stated in the previous chapter, one limit of the extended PAC Framework is readability. The number of **elements** make the visualization(s) hard to comprehend. However, we noticed that nearly all elements of the current framework have the potential to be **extended into their own framework**. For instance, problem-based learning (PBL) in groups seems to systematically contain different high level processes like building common ground through negotiation of different visions, identifying missing information, information retrieval, generating solution approaches (brainstorming), filtering and selecting these approaches, before implementing and testing, and finally evaluating them. For instance, while working on the literature review of part II, all activities we could identify in the (now) 62 studies of our dataset, can be described or are part of this activity sequence. However, PBL is only one educational approach where collaboration is a central element. Jigsaw or Think-pair-share are educational activities around collaborative learning. As such, extending the PAC Framework towards this dimension seems important to combine processes and practical pedagogical formats. The documentation of the latter has been attempted through visual languages like COLLAGE, attempting to equip the different actors of the TEL community with a common language (Nodenot 2007), itself a topic that has been acknowledged as central by the CSCL community very recently (Baker and Reimann 2024).

We also would like to integrate data about **contributions** and **authors** into the framework, as to give its users the possibility to identify key contributions and authors of each subfield. This in turn further impacts readability, if such information is to be added to the current version. In part II and IV of this dissertation, we demonstrated how the PAC Framework could be used for **documentation** purposes of experiments, both for documenting setups (activity, experiment and tools) and results. The latter potentially change how collaboration or collaborative learning is understood, thus changing the framework itself (through new insights, establishing relations or detailing the many frameworks it refers to, e.g. indicators of analytic frameworks). From a computer science point of view, the framework can be considered a **data structure**. This structure has to be flexible enough to be modified fundamentally, and it also requires a **method of**

exploring and reading it in a easily comprehensible way for CSCL researchers.

Data Structure: Given the current structure and ambition of the existing framework to model collaboration, an **ontology** appears to be an adequate choice. Ontologies describe how concepts relate to each other through the use of triplets (concept – predicate – concept). Through this approach, the PAC Framework could be transformed into a data structure that also could be exploited computationally.

Use cases: Using an ontology as a blueprint for documentation (for example through the use of a submission form) not only streamlines and guides the researcher’s experiment setup, but also enables the community to **store** information about different studies like sample size, age etc. in a standardized way that lets the community compare similar studies.

Furthermore, results of experiments could be documented using the ontology, describing how the different collaborative elements interact with each other. If stored in a common database, a visualization of the ontology could display valuable information about the studies that support the relationships between and the properties of the different concepts. This way, contradiction or confirmation in the framework could be highlighted, leading to studies explicitly targeting contradictions or bolstering findings from exploratory studies. This also means that the ontology itself is no static artefact and issue to change through the contributions of the community. Finally, datasets could be annotated and submitted alongside experimental setup and results to increase the possibility to cross similar datasets or extract multiple insights from the same dataset through different methods and research questions, as has been outlined by Hmelo-Silver and Heisawn Jeong in their chapter “An overview of CSCL methods” in *the International Handbook of CSCL* (Cress *et al.* 2021).

Beyond identifying new research questions, such an ontology-based dataset can provide valuable insights into the diversity of research by topic. Statistics about the quality of relationships between concepts could be made available, alongside research diversity (number of different authors / labs etc.) per subject. It also would provide an improvement to keyword based literature reviews, since linguistic clarity would be increased if authors were to use such an ontology in their studies.

Processes: If the extended PAC Framework is to become a dynamic ontology (in the sense that it can change depending on study results by its community), a process is required to regulate and validate contributions. Contributions that challenge existing relationships may first be displayed accordingly, but only change the ontology itself once

sufficient evidence is gathered. The criteria for “sufficient evidence” has to be defined by the community (e.g. given a relationship in the ontology supported by two studies, if n studies with properties x,y,z in a,b,c activity contexts contradict this relationship in a metareview published in journal j , the change translates into the ontology itself).

Similarly, conditions have to be defined for contributions to be recorded in the ontology-powered database: should conference papers be included or only journal contributions? If the ontology is to be dynamic, different versions of the ontology will be referenced and used by the community at different moments in time. This is a challenge that already exists, since conceptual visions are informed by experimental results. Using versioning systems that highlight changes and potentially can take into account such modifications for comparability could help address the complexity that comes with it for the research community.

Entities: As is the role of a journal to maintain scientific standards in its publications, an entity or a collaborative procedure has to keep track of the different contributions and keep different versions of the ontology to which researchers can refer to in their publications. An alternative to a central organization would be a peer-based validation: depending on the region within the ontology, submissions could be anonymously sent to specialists of the area to validate or enter into a conversation about the modification it proposes to the ontology with the author. Once validated, the change could be integrated and a new version of the high-level ontology be published. Projects such as Gene Ontology could serve as inspiration for the setup of procedures and submissions (The Gene Ontology Consortium 2019). Given the many specialized frameworks in the PAC Framework, the latter approach appears to be more promising. However, if changes to the ontology are to be made by many groups in parallel, tools are required to avoid conflicts and parallel, incompatible versions.

Tools: For adoption of an ontology, the interaction with it has to be accessible: Firstly, to the **validators** of changes to the ontology and secondly to the **readers** of the ontology and the researchers **documenting** their studies with it.

For the **validator** user group, a variety of tools have been developed to create, modify or read ontologies, but the usage of which requires skills and knowledge about ontologies and the tool itself. Recent research on the use of large language models as assistants for such intervention has shown that these tools might help “alleviate the knowledge acquisition bottleneck, for ontology construction” (Babaei Giglou *et al.* 2023). Demelo and Sedig (2021) state that “when the size and complexity of a domain rises, so too does

the complexity of its ontology. As a result, ontological datasets can become very large and complex, supporting countless complex objects describing ontology entities and relations. When interacting with highly complex spaces like ontologies, the limitations of human cognition can create a bottleneck in human-facing analytic workflows”. Accordingly, we see potential in the use of generative AI tools to support such modifications and facilitate the interaction with it for the validators.

The limits of cognition are also of concern for the **reader** group: Simply visualizing the entire ontology in one graph-like structure seems unpractical, as the problems of visualization of the current PAC Framework have demonstrated. There might be potential for the use of AI to interact with the ontology through natural language, assisted through partial dynamic visual guidance. The successful use of custom learning paths (Cheng *et al.* 2018) leads us to believe that there might be potential to propose linear learning paths to users depending on their existing knowledge, thus providing users with “angles” from which understanding the high-level ontology is most likely to be the most efficient depending on their background.

Finally, **documentation** can be assisted through online forms where researchers can enter the parameters of their studies (objective, target, indicators etc.) with a possible validation logic based on the ontology (e.g. if a collaborative indicator is a bad fit for the data type the user desires to analyze). Documenting the results and datasets could also occur on a dynamic form with validation based on the data submitted during the experiment setup documentation stage.

Use Case Example: The following is an example how we envision the use of the extended PAC Framework in CSCL research:

Researcher A wants to identify a pertinent research question in CSCL. A public website displays the CSCL ontology and with it, contested links between collaborative processes. Researcher A identifies a link between the tool type “interactive tabletop” that has been found beneficial and detrimental for behavioral awareness in two concept mapping scenarios. Researcher A investigates the contradicting link by comparing the two underlying studies. Researcher A notices that the two studies relied on two different analytical frameworks and defines the research question on the applicability of the used indicator in the given context after consulting the dataset of both studies. Researcher A sets up an experiment to test the used indicator with the help of a design framework for tabletops and another one for collaborative activities. They document the setup through an online form linked to the current ontology. The tool saves the data as preregistration and serves Researcher A

as a check list for the data of their participants, tool and activity. The study is conducted, researcher A publishes their results to the ontology server, simultaneously publishing their dataset. The ontology now counts three studies for the link tabletop-behavioral awareness, visualizing slightly differently due to the new results. A new link marked as contradiction between the contested indicator and the analysis of behavioral awareness.

The framework is thus an artefact to research collaboration, and a collaborative artefact at the same time. It is to the image we envision the CSCL community of the future: Researching collaboration in a collaborative way. Beyond the application as a collaborative knowledge building artefact, the ontology could serve as an entry point (just as in collaborative tools) into the community for new members. The new member's perspective as one of legitimate peripheral learners (Lave and Wenger 1991) is valuable to establish potential learning paths for other researchers of their domain that are concerned with collaboration in their own experiments, but whose main field is outside CSCL. Indeed, the CSCL community has seen a decline in contributions in the last years (Damşa *et al.* 2024) and providing clear entry points to central resources of the community could potentially increase attractiveness for newcomers. In the tradition of collaborations of this kind, we hope to further consolidate a Joint Problem Space for CSCL (as well as a social space). Who, if not the international CSCL community, would be better suited to conduct and excel at such a collaborative endeavor?

Research Collaboration

The CSCL community, in particular, has to keep track of changes in the dynamic domain that constitutes CSCL, and a regular workshop on the different conceptual components of CSCL should be part of the community's habits. Pre-conference workshops are held for instance during the annual ISLS/CSCL meetings, but there is no regular instance of workshops on the different areas, such as transitivity (one symposium in 2023) to maintain continuity. Such regular exchanges are particularly interesting in light of the framework we propose as a common artefact to reflect on new theories and changes to challenge existing perceptions. Given the multi-facet nature of collaboration, as lined out in the extended PAC Framework, it might be of interest to organize special interest groups (SIG) along the different areas - social space, knowledge building etc. along with analytic frameworks providing indicators for analysis. To maintain overall collaboration, exchanges between members of those groups (similar to the Jigsaw practice) could be organized between those SIG meetings to maintain common ground and coherent conceptual links for interrelated

subjects.

15.2 Towards A CSCL Software Design Framework

Given the central role of the activity type (Troussas et al. 2023), one important step forward for this work is to include this parameter into the analysis. Given the variety of activity types and contexts, it would be crucial to increase the corpus of studies included in the literature analysis. We discuss two other perspectives in the following subsections: The potential for a collaboration around the development of the PAC Mapping and a software framework to share and build on existing software with one key objective to enhance repeatability of studies.

15.2.1 Research Collaboration

As with the PAC Framework, the current mapping can be extended and become a community artefact. To this end, we envision to publish the **dataset** behind the meta-analysis (which has since grown to a total of 63 research papers) as an open access data paper. The dataset contains unexploited dimensions such as the lab setting, the activity itself, a categorization of the activity descriptions, whether the paper describes multiple studies, and experimental conditions (sample size, average age etc.). On a larger scale, we intend to inspire collaboration around shared datasets and artefacts. Just as with a common collaborative ontology, shared artefacts like this require a strategy of versioning and coordination to maintain coherence. If the ontology enters existence as described in the previous paragraphs, this work could simply become part of it and the efforts to provide a collaborative workflow for the ontology artefact can benefit the management of collaborative data papers.

15.2.2 A Software Framework

As presented in part III of this manuscript, the fact that CSCL researchers use custom software for custom activities makes it hard to repeat studies. While software can be distributed at negligible costs, it does not seem to be common practice. In a survey among the 2020 CHI conference participants, Wacharamanotham *et al.* (2020) have found that less than half of all participants who answered the survey (34% of a total of 700 participants) disclosed their experimental software and less than 15% did so for their

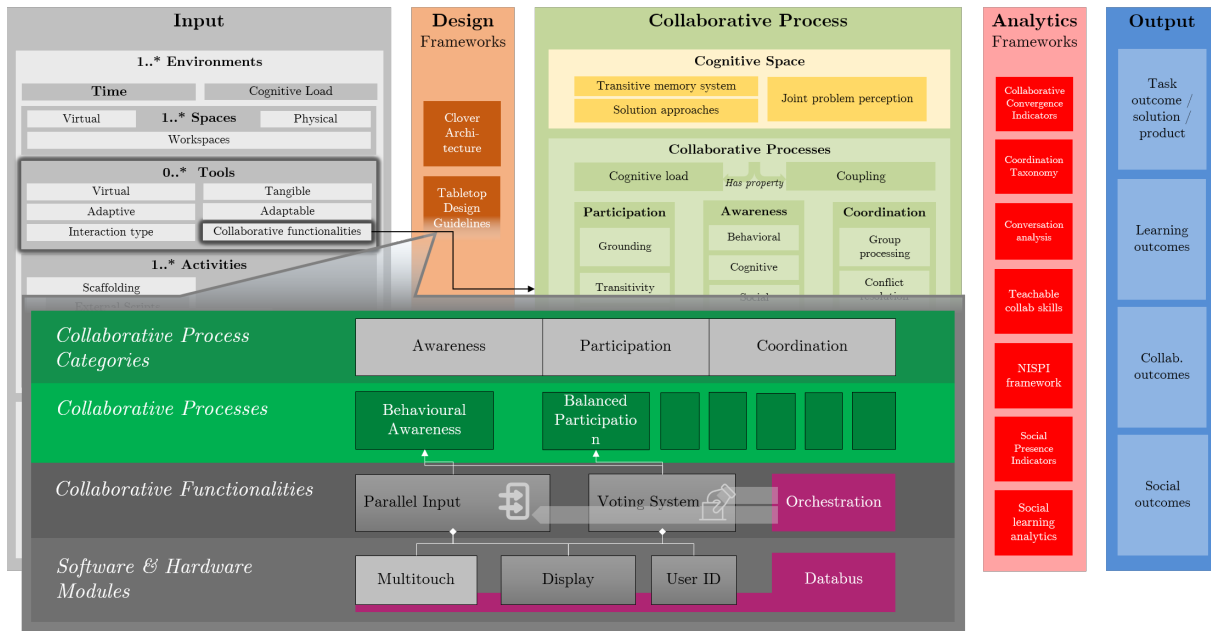


Figure 15.1: The architecture of a modular software framework for collaborative functionalities consisting of a conceptual layer and the software implementation part and its position in the PAC Framework.

datasets.

Beyond the problem of repeatability, given the complexity of collaboration and CSCL analysis, we argue for the need of a common, modular software functionality framework. A common framework could contribute to a better cross study analysis, required to determine the impact of individual functionalities, or combinations thereof for collaborative settings in a modular approach: Ideally, researchers reuse existing functionalities, which they then combine with newly developed functionality (which in turn can be published for future use and improved repeatability). However, such a framework faces major challenges, prominently standardization and flexibility to hardware changing at a fast pace and the double role that software plays in CSCL. Indeed, CSCL software is intended to both support collaboration while providing data to analyze it, and the latter more recently, for real time feedback to the collaborators themselves.

Accordingly, we argue for a multilevel framework that on its most abstract level remains agnostic to a particular technology and describes collaborative functionalities. The lower level would constitute the actual software implementation (figure 15.1). As such, it would qualify as a design framework on the tool side of the gradient between tools and collaborative processes, as opposed to the PAC mapping, situated closer to the concep-

tual level of collaborative processes. As an example, figure 15.1 describes the collaborative functionalities “Parallel input” and “Voting system”, both requiring a display module, but only parallel input requires multitouch, whereas the voting system requires user identification. This is to show that different functionalities can have overlapping requirements for hard- and software modules. All functionalities can be used for orchestration. Ideally, every functionality can be dynamically configured to show on the interface depending on different triggers defined in the orchestration module. Such a framework would be, from the perspective of the PAC Framework, situated at the intersection of tools and collaborative processes (see figure 15.1).

The framework would be hosted on a forge for researchers to select, depending on their needs, their functionalities and develop new modules and functionalities or new variants from existing modules, making differences obvious and allowing for a detailed argumentation why their setup does or does not differ from previous experiments with similar software (reinforcing argumentative linkage to previous and future work). To ensure interoperability, standards on module interfaces have to be defined beforehand. Given the requirement of modularity and universal applicability, the technology has to be chosen accordingly. Currently, web based libraries, for example, offer the required flexibility in this regard (multimedia and screen size support). Modularly organizing functionality could, in a future version, allow for the rapid prototyping of groupware. If standards on configurations of collaborative functionalities are established, researchers or educators ideally should be able, through the use of a dedicated tool, to assemble those modules into codeless groupware deployable on available devices. Such tools already exist for customized, hardware agnostic Linux distributions in the context of embedded hardware (Charreye 2014). Giving educators and researchers the possibility to build their own groupware also may help the creation of a community that comes up with new functionalities or new innovative ways to combine them.

A module for recording usage traces can in turn feed open datasets for researchers to establish to what extent combinations or individual functionalities support collaboration. Such an approach would be an extension to Marfisi-Schottman (2023)’s PI-DBR approach, in that it not only includes educators in the design process but makes them designers and contributors themselves. Delegating any supplemental work to educators is naturally problematic since educators traditionally have a high workload. Consequently, assistance in the authoring process through a recommender system based on existing research results about combinations of collaborative functionalities seems like a necessary feature. Fur-

thermore, such a community would naturally strive to demand or implement more than the 20 functionalities we could identify in this dissertation, making it an interesting approach to develop cooperatively a more comprehensive vision (reuniting practioners and researchers alike) that the one presented in this dissertation.

15.3 Dissemination of SPART

In this section, we highlight the perspectives for the prototypes of the SPART interaction. Initially, we highlight how we intend to spread adoption with the goal of building a more solid experimentally backed knowledge base concerning its collaborative benefits. We then discuss technological perspectives for the improvement of the current prototype and potential alternative technologies. Finally, we discuss potential applications.

15.3.1 Open Science and Distribution

Accordingly to the design method SPART was implemented in part III, we intend to publish the 3D files on maker platforms like thingiverse.com and hand over the project to the maker community. To this end, blogposts detailing the construction of SPART and an instructional videos on the largest collaborative hardware community platform, hackaday.io, are intended to raise awareness around the project and its technologies (notably on the magnet based rotary encoder that might be of use to other DIY projects). The code will be published on github.com, the largest open source forge, and HAL, a multi-disciplinary open archive for the sharing of research. The intention behind this endeavor is to make SPART available to two publics:

1. Interested hobbyists to explore possible applications we did not consider, the development of new modules (software and hardware) and a more robust design than the current version.
2. Fellow researchers to test the interaction with minimal upfront investment, to further experiment the technology in different contexts and focus on study design.

15.3.2 Evolution and Development of SPART

During this PhD, we have developed and tested 18 variants of prototypes, out of which two fulfilled the list of eight requirements presented in part III. The shortcomings of both

prototypes are their moving parts that typically require maintenance after use in environments with dust or dirt particles and a longer setup time when in mobile environments (attaching the end of the string(s) to the device). Ideally, SPART should use internal sensors or should not require physical connections to a reference point, the latter of which is one of the main shortcomings at the time of writing. Mechanical variants are unlikely to overcome this issue. Thus, we recommend further research on the acoustic variant of SPART. We are confident that the interaction type may become a wireless reality through either SPART-AC or the development of new technologies (such as robust and low-priced augmented reality goggles for example).

Mechanical Variant SPART-ME M

To improve aspects of usability and DIY, we envision a one-time calibration phase where the user's only intervention consists in turning the arm (measuring relative angle) from one extreme to the other and the device, through polynomial regression, creates a model based on the extreme values recorded or adapts an existing model of the magnet to the measured data. Furthermore, the firmware of the operating system should reflect the flexibility of adding custom hardware modules to the prototype. The top part of SPART-ME M is removable and can house additional sensors and microcontrollers that can be connected with the main controller through a standard I2C bus. This feature allowed us to add an NFC-reader for our second field study for instance. Other sensors, such as gesture controllers, gyroscopes or buttons make SPART adaptive to different contexts. Indeed, having the possibility to add additional microcontrollers and sensors to SPART enables users to customize SPART rapidly. The hardware modularity should be accompanied by a similar software architecture: Users should be able to add software modules for capturing data from such hardware modules without modification to the core code of the prototype's system. In order to achieve this, it should be possible to create configuration files that provide information on the module's I2C bus address, how and at what interval to read the data as well as procedures on how to process and expose data as a custom BLE service¹

On the hardware side, the issue of attaching and detaching the string easily to the mobile device has to be addressed. Currently, a custom device shell with a flexible hinge

1. "A service is a collection of data and associated behaviors to accomplish a particular function or feature. [...] A service definition may contain [...] mandatory characteristics and optional characteristics." [Bluetooth Core Specification v4.2 Vol. 3](#)

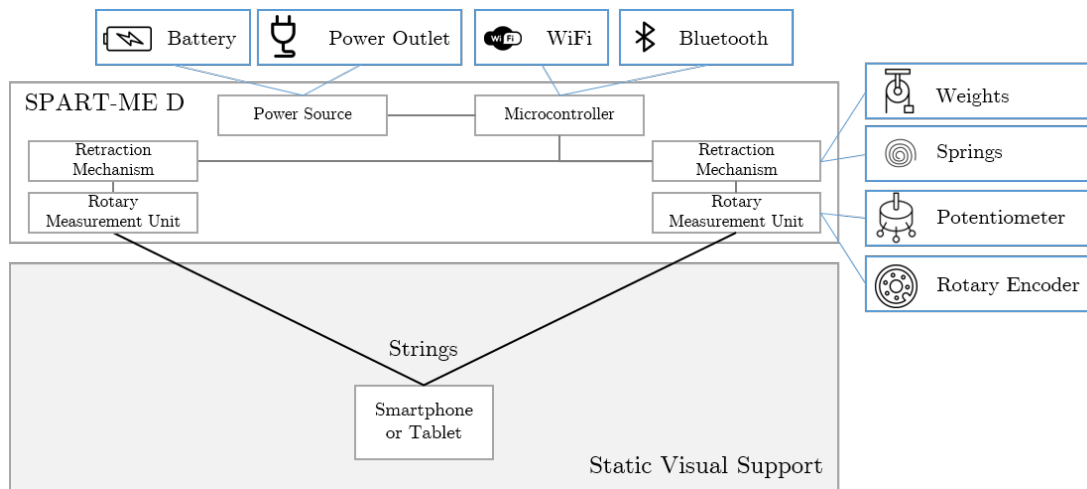


Figure 15.2: Modular hardware design for two-string SPART prototypes. Icons by flaticon.com

holds the end of the string attached to the mobile device, but the hinge is a fragile part that has been broken when carrying the mobile device in a pocket. The pushbutton for attaching SPART to the surface could be used in the shell for a more integrated design and easier attachment and removal. Another possible development is an additional axis to the arm, enabling 3D localization. This would require as little as a single additional sensor but a redesign of the arm to accommodate the axis.

Mechanical Variant SPART-ME D

We presented the two-string prototype as a means to augment horizontal and vertical surfaces of various sizes. We have developed two prototypes for now: one based on 10 turn potentiometers (1) and one based on the custom design of magnet based rotary encoders and weights (2). What has not been designed (yet), is hardware that mirrors the modular approach in figure 15.2. Ideally, users can choose from different retraction modules, sensors, attachments and casings to compose and assemble their variant without glue or other materials impacting reparability.

The vertical variant can be used to create affordable smartboards (in conjunction with a projector) and augment large wall mounted maps. Strings and weights configured to counterbalance the weight of the attached device mitigate muscle fatigue or fear of breaking the device as experienced in the experiment of Sanneblad and Holmquist (2006).

Acoustic Variant SPART-AC

The current acoustic prototype is a proof of concept for the acoustic technology. Albeit inaccurate, heavy, susceptible to ambient noise and missing real-time position updates (a two second lasting white noise has to be emitted at each location update), we are confident that these issues can be resolved (for instance by collaborating with the LAUM laboratory). Since the start of the project, three different student groups have worked on the prototype. With each group, considerable progress has been made. At the time of writing, a fourth group of students has achieved a considerable improvement in fluidity (with a theoretical update rate of 5 Hz). Since we concluded through the analysis of the physical properties of soundwaves that accuracy and fluidity fulfilling the requirements are theoretically possible, the current prototype (now eight MEMS microphones integrated into a sturdy aluminium platform to host the static surface to augment) constitutes a development tool for future student groups to improve algorithms and sound choice. Being able to use internal sensors and not having any physical connection or external module attached to a conventional smartphone or tablet is a major advantage of this approach. Once the requirements of accuracy and fluidity are met, research on affordable components can be carried out, since the current acoustic prototype does not fulfill the accessibility criterion (200 € production cost and necessity of CNC machinery).

Other Prototype Concepts

Our literature review on technologies revealed seemingly promising alternatives to the mechanic and acoustic variant, most prominently, the magnetic approach. During this work, we discovered the (commercial) EMF tracking project [AmfiTrack](#) using generated magnetic fields for “low cost yet high precision” localization. Not only is the approach advanced, but the mobile device would need a receiver to capture the signals. While not impossible as a standardized USB-C extension, upon request for a development kit we were informed that the price tag was currently 3500 € (06/2023), which, if implementation proved to be possible would still be very far from our definition of affordability (50 €).

Likewise, we contacted the researchers behind the [Electrick project](#) (using electric tomography for localization) to investigate whether any commercialized product was available or if plans and software was available. While the circuit design and software are [public](#), we have been informed by the authors that “Even though the circuit designs are available, I suspect there will be a steep curve in getting this up and running” which is

likely to impede with the accessibility requirement. Among the optical variants, the only robust technology we would consider, is the one inspired by a speaking pen / QR codes (a CMOS camera module attached to the mobile device reading position codes printed on the surface, invisible to human vision). We contacted the developer of an implementation for [robot localization](#) who confirmed a good outdoor performance for the readability and durability of the IR codes, thus increasing the potential of the requirement “robustness”. Another challenge for this approach is the development of a circuit board powered by the mobile device. Finally, given the missing availability of infrared ink cartridges for printers (impacting DIY), testing would have to reveal if ink at the limit of the visible spectrum or methods of stenography (hiding visible codes in the image itself) could help overcome this restriction.

15.3.3 Applications

Mindwalks

In addition to collaborative situated learning, SPART may be of interest to support memorization of learning content in other contexts. For instance, the potential of using spatial patterns to better remember information has been exploited by mnemonics (McCabe 2015). Associating information to spatial positions or places allows to remember far more information than without this technique (Loki method). During the training phase, users of the method associate information with places. During the retrieval phase, users imagine themselves in one of these places (or physically move there) which scaffolds the retrieval of associated information. McCabe studied the use of maps to support “mindwalks” and reported positive results. SPART could support such map based mindwalks by overlaying the map with scaffolds to render the abstract map presentation more vivid or provide help for content that has been forgotten. Being mobile, support for mindwalks is available for homework or out of school activities.

SPART-based Educational Environment

The Loki method (introduced in the previous subsection) is ideally used in a regularly frequented environment. A very regularly frequented environment by students is the school building and its surroundings. Consequently, learning content could intentionally be taught in specific parts of a school (like biology, due to the need for specific equipment). Students could be encouraged to discover virtual learning content associated to locations

with augmented reality in such dedicated areas, fostering autonomous exploration. SPART could scaffold such a learning approach by providing a device that supports small learning groups through collaborative scaffolding (as demonstrated in our second field study with NFC tokens). Thus, the school's architecture can morph and support into the creation of what has been coined a "mindpalace": an extension of the imaginary mindwalk into a mental structure where information can easily be recalled (Sims *et al.* 2022). This approach could further be reinforced through the availability of a remotely available virtual representation of the school accessible in VR or through a personal computer or mobile phone with SPART for homework etc. Since SPART is ideal to augment maps, maps of the school building constitute a perfect support for homework activities. In such an environment, gamification elements, such as custom hardware modules for SPART, new functionality or support could further foster interest in "new" technologies and STEM subjects such as 3D printing, computing and electronics. Student designs and extensions can be used to motivate successive generations of students for challenging learning tasks. The authors of such designs could be involved in deciding to which learning task their design should become a reward, playfully involving students in their own curriculum. SPART would thus act as a central educational artefact that accompanies students throughout their academic career, integrating the students' smartphones in a meaningful way in their learning.

Augmented Games and Industrial Application

Beyond the educational context, SPART can be used to augment and provide interactive real-time components or evaluation and feedback methods for classic board games. For instance, using mobile devices in conjunction with games like [MicroMacro](#) (a game on solving riddles on a large, crowded map) could add real-time and interactive elements, dynamic scaffolding and feedback.

Another application is industrial documentation and feedback of machines. Augmented and virtual reality are widely used in the context of an industry 4.0 (Olwal *et al.* 2008), providing digital twins of their machinery to simulate processes or facilitate trouble shooting or assistance. SPART could intervene through the visualization of the potentially complex interior of industrial machines with a smartphone placed on top of the machine in question.

15.4 Long Term Perspectives

This section describes potential studies following our field studies and observations in previous chapters. We describe potential study setups for research on mnemonics, awareness, the use of multiple devices, scaffolding, human-computer interaction design and collaborative learning.

15.4.1 Studies on Mnemonics

In order to sustain or refute the hypothesis that SPART can act as a facilitator for map-supported mind-walks, further field studies are required. We hypothesize the advantage of SPART based on our observations of its low cognitive load and abilities to provide a pertinent human-computer interaction to augment mindwalking maps. An experimentation could consist in a memory retrieval task. The task would require participants to associate a list of items to a physical location and then go for a physical walk. They then would be separated into two groups. The control group would do a mindwalk just with a basic map while the test group would use SPART with either or both of the following functionalities:

1. Increased fidelity compared to the basic map
2. Hints depending on position and item in case of difficulties

The participants would then have to answer two spaced out post-tests, without any support, in order to determine if the impact of SPART on this type of activity is significant. Such a study should be particularly interesting for vocabulary learning, where physical presence in situated environments have shown positive impact on retention of vocabulary (Saavedra *et al.* 2024).

15.4.2 Group Awareness

In the first study, we observed that SPART acted as a visual anchor for group members temporarily leaving active group work. This appears to have reduced synchronization time, after a coupling phase. However, coupling as a concept in CSCL is recent and therefore still subject to research. More experiments with SPART in different contexts are thus required to strengthen (or weaken) this hypothesis. Notably, it requires the identification of coupling in video streams of further experiments. Moreover, the process of awareness, for which only its absence can clearly be observed (questions etc.), calls for individual

interviews with students in a timely manner to unveil their inner processes and state of group understanding upon return.

15.4.3 Multi-device Experiments

Our experiments have been conducted with one SPART device per group. Many configurations in other studies contain multiple, personal devices and a shared central device. Nevertheless, these configurations do not include location aware devices for personal use. From our point of view, it would be interesting to compare individual devices without augmented reality and classic augmented reality for individual devices with multiple, individual SPART devices tied functionally to the same surface as the shared device. Such studies could extend the work of Rädle *et al.* (2014)'s HuddleLamp and provide insights whether personal devices are used as personal devices because of their affordances or if the notion of a personal device itself, if given the option, is a dynamic concept varying with task and group perception. For instance, if using the personal device's screen can help view a big virtual object when put side by side with other location-aware devices, will the personal device become a shared device (meaning other users will interact with it)? Users have been observed to make creative use of the provided affordances and beyond the intended use by their designers. From a more abstract point of view, this brings us back to the question of scaffolding: Allowing creative use may support advanced collaborators in their work, but new users might need the limits of the tools to free cognitive resources for the activity itself, another question of interest in itself.

15.4.4 Scaffolding

Scaffolding has been implemented through intermediary visualizations between the static, abstract support and reality. For instance, in study 1, we could observe a group using a more detailed map than their own colored map (meant as a debugging feature) to better understand the mechanisms behind tectonic plates. Such an intermediate, scaffolding layer of information was also suggested during a workshop with educators to make preschool children gain understanding of maps and their relation to the real world by adding a layer with more information or a 3D scene for comprehension. We see an opportunity to experiment such potentially dynamic scaffolding with SPART. Initially, groups could be given an option to manually activate such overlays together with a control condition in which paper maps or transparent overlays are handed to students, to compare SPART to such

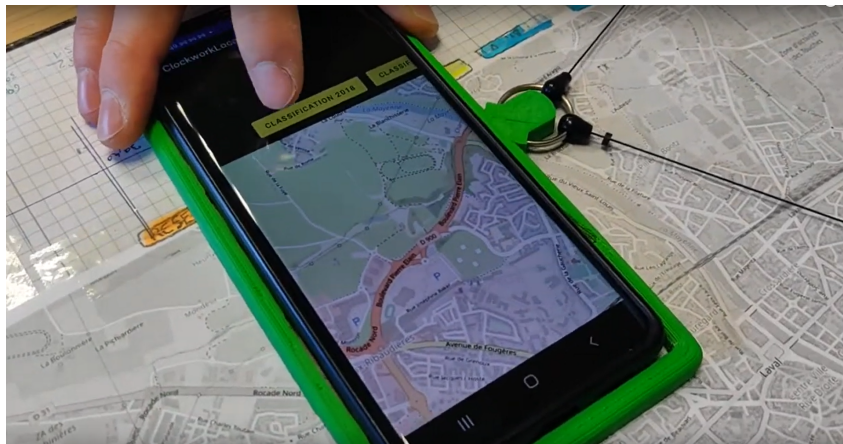


Figure 15.3: SPART with sketched buttons that become interactive when the device is placed at their position on the map

more traditional options. Such an exploratory study could analyze the degree to which there are circumstances favoring the introduction of scaffolding (timing of scaffolding) and how the flow of the activity is impacted by such a mechanism.

The mechanism could, in a follow up experiment, be tied to tests during the activity instead: Layers get sequentially unlocked if a group fails to correctly identify a landmark on the map (known as backward fading) for example, or given results from the previous study, options for intermediate layers could be unlocked automatically to correct early on faulty mental representations.

15.4.5 Alternative Interface Design

SPART (and other dynamic peephole interfaces) allow for the use of their position and rotation for the exploration of virtual content instead of more traditional gestures on the touchscreen. Thus, gestures in particular and touch in general is available to take on other duties than navigation. In public demonstrations of SPART we have shown sketched interfaces (buttons) on the underlying static support as visual cues for the interface outside the display. Interfaces with many elements are typically reserved to bigger screens, due to the restriction of screen size on mobile devices (figure 15.3).

In collaborative settings, tools could implement complex interfaces that become interactive when the device is positioned on them. Students could preemptively reflect on and plan possible interaction sequences (as has been observed in study 2) with the sketched/printed interface on the static support. Meanwhile, other group members can

continue to use the device to augment other parts of the static support, fostering planning and reflection among group members. A study could entail a simulation program with a large number of parameters whose interface elements are printed on the support to study if those visual cues help the planning and reflective processes. For instance, Jetter *et al.* (2011)'s facet stream study included a hotel selection and reservation task which could be ported to SPART in order to investigate whether the absence of the tangible tokens used in their setup could be compensated through the purely visual nature of a printed interface (and user annotations to the static support). If the mobility of the tangible tokens is confirmed as the key element supporting user interactions (in the study of Jetter *et al.*), the use of mobile NFC tags (to be read by the mobile device) could be experimented.

15.4.6 Learning of Collaboration

For study 2, we documented the effective integration of a personal token-based system that gave complementary functionality access to each group member. This was a way to foster positive resource interdependence, one of the possible input properties of the collaborative process. We observed planning and discussion around the use of these tokens, leading us to believe that the functionality “activity reinforcement” identified in part 2 has the merit to be further detailed among the different types of positive interdependence that can be implemented tool wise. In our scenario, we implemented activity reinforcement through positive resource independence, but in other variants of positive interdependence, for instance inter-group competition (positive outside enemy interdependence), implementation in tools (for example through a scoreboard) varies accordingly. Implementing such positive interdependences can support collaborative processes to free cognitive resources for content oriented, cooperative learning. Likewise, SPART can be used to sensitize students to collaborative processes, consequently enhancing learning of collaboration.

15.5 Contribution to the SituLearn Game Model

This chapter describes the potential contribution of our work to the SituLearn game model. We detail the current model's structure and propose potential extensions and modifications in the second half of this section.

15.5.1 Current SituLearn Model

This dissertation is part of SituLearn, an ANR project for providing authoring tools for teachers to prepare field trip games that can be played on students' mobile devices. The model behind SituLearn has been developed with educators of different fields (Marfisi-Schottman 2023), following the PI-DBR method. In its current version (figure 15.4), the model features collaborative elements, most notably, the “Collaborative Game” concept, associated to a team and milestone. Each milestone contains several Situated Game Units (4 to 10). The team members must coordinate their efforts to distribute these game units among themselves in order to win the most points in the allotted time. In practice, when a group of students encounters such a collaborative game element at a POI (Point of Interest), the collaborative activity resides in the development of a **strategy** to distribute "game units" among group members in a way to optimize for time and outcome. The outcome is an answer to a final question of the collaborative game that can only be answered if all team members succeed in their individual game unit.

The current model thus already features elements of positive interdependence in that team members collect, during their individual game units, information necessary to answer the overarching milestone question. This conception also induces individual accountability, a key feature of cooperative learning as noted by D. W. Johnson and R. T. Johnson (2009). Marfisi-Schottman (2023) mentions the possibility of making “team scores available to all teams to encourage [...] competition”, another form of positive interdependence (common Outside Enemy Positive Interdependence).

15.5.2 Extensions of the SituLearn Model

Following our work, we propose an extension to the existing SituLearn model in figure 15.5 by mapping the collaborative entities to the PAC Framework. We also propose some minor modifications to the existing model.

PAC Framework Mapping

The Input part of the extended framework contributes the necessary elements for a “CollaborativeGame”: a collaborative activity with elements such as a scaffolding entity (typically the educator), an appropriate task etc. This activity is however designed in such a way that it uses the “SituatedGameUnits”.

The collaborative input part further provides the tool entity, defining collaborative

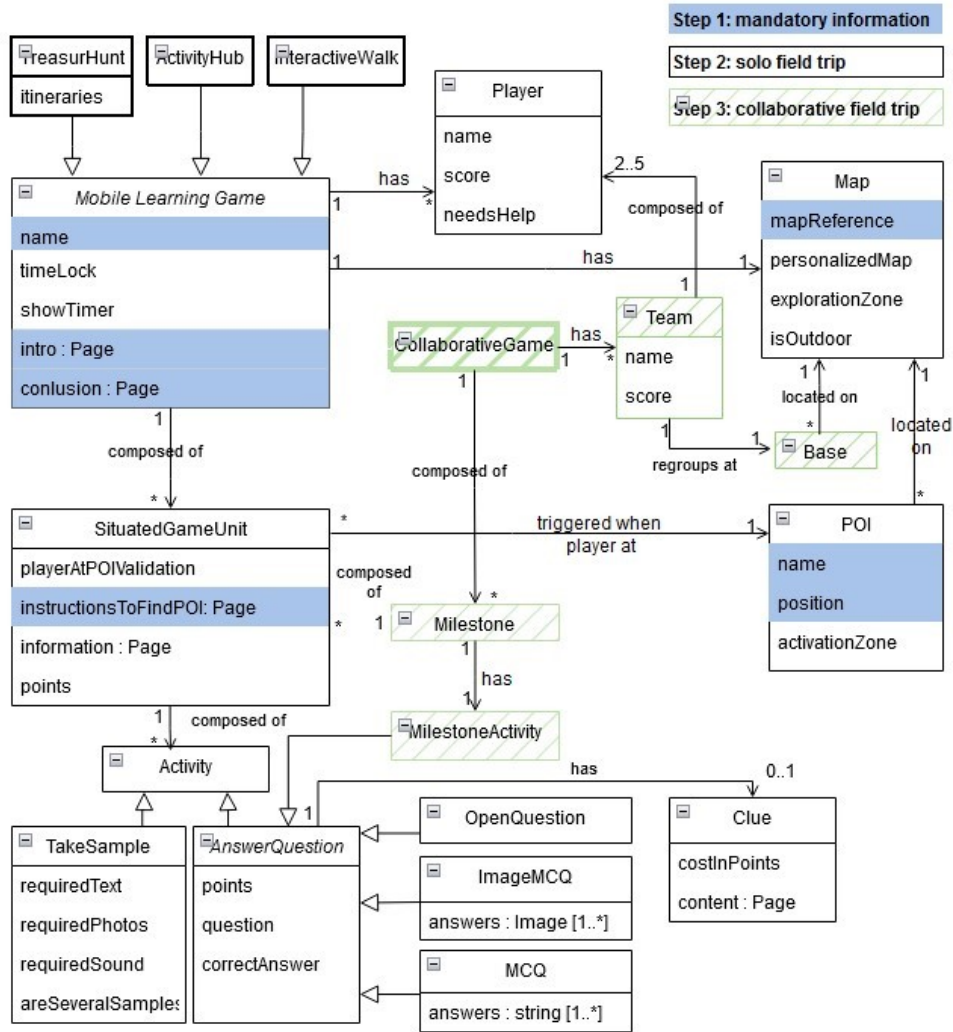


Figure 15.4: SituLearn Game Model as in Marfisi-Schottman, 2023

functionalities and interaction types (e.g. SPART). The direct link that can be established between a tool such as SPART and an entity of a situated learning model highlights how particular interaction types suited for collaboration have particular interest for other learning types as well (in this case a model of situated learning featuring maps). Furthermore, the framework input part provides task and pedagogical objectives that map to the collaborative output: should the “CollaborativeGame” support the learning of a skill, a collaborative skill or social relationships? Other elements, such as the “Participants” or “Space” elements from the PAC Framework map to the “Player” and “POI” entities of the Situlearn model.

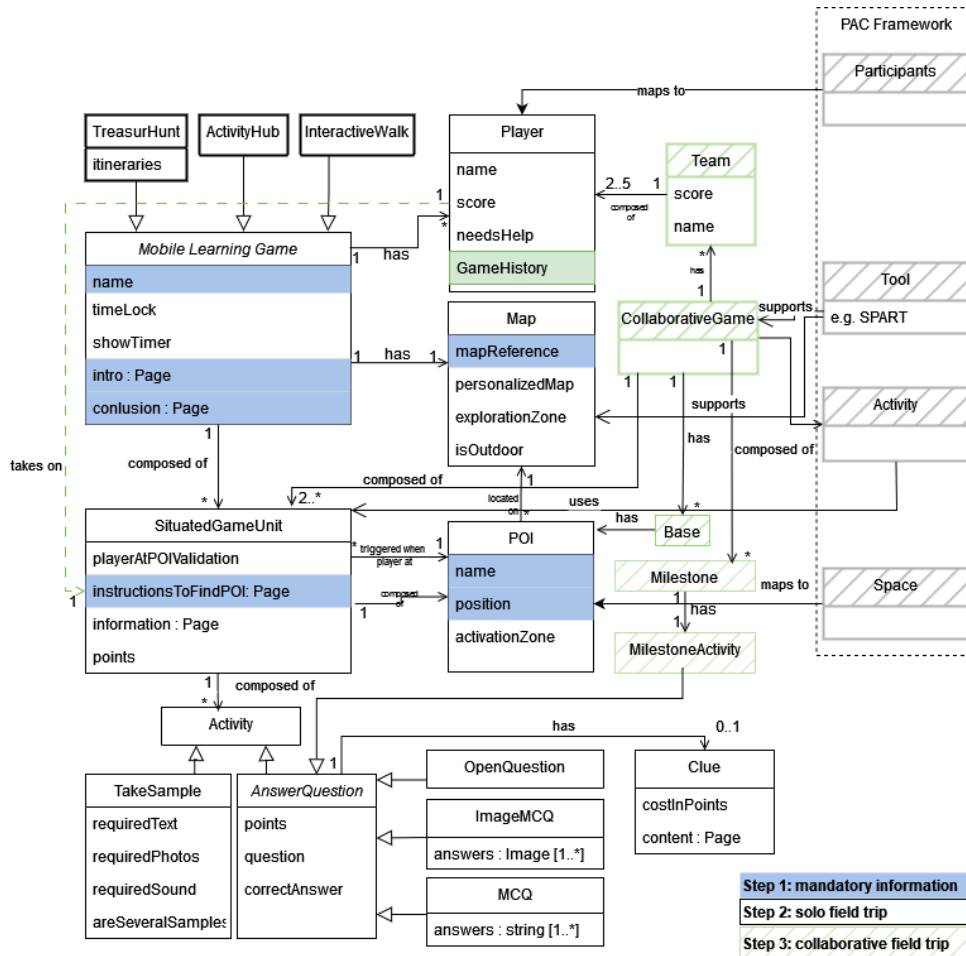


Figure 15.5: SituLearn Model with collaborative concepts

Modifications

Firstly, instead of a collaborative game being located on a map, we mobilize the concept of a POI associated to a collaborative game. The aforementioned positive interdependence in this model can be extended. While currently limited to distributed information available to students during individual Game Units, if information about a player includes a history of individual game units, educators could design collaborative games where the same students repeatedly are confronted with similar problems and become, over time, specialists on the problem type. Then, a collaborative game can be conceived that assigns such a task to another team member, requiring explication and peer tutoring, similar to what the jigsaw method is intended to achieve. Explaining acquired knowledge tends to deepen it (Lombrozo 2006), all while the acquisition through a knowledgeable peer can

benefit at the same time the learning process (Hattie 2011), given appropriate implementation and context (Cochon Drouet *et al.* 2023). To this end, we added the attribute “GameHistory” to the player concept to target players with situated game units and allow for the aforementioned jigsaw situation. To support the social space creation and analysis of collaborative skills of players, for instance, learners could receive credits for special learning efforts outside situated games and use such credits instead of the group’s points for clues during the individual situated game units in the collaborative game, sacrificing some personal benefit for the performance of the team. Such actions can be used both as motivators and indicators for the presence of a functioning social space among the group (Bonebright 2010b).

15.5.3 Final Thoughts

In the spirit of the double role of any tool for collaboration (analysis and improvement), the educator should be able to have a record of their interventions for testing different intervention strategies and learn from previous interventions. On a larger scale, data from orchestrating educational experiences is highly valuable for studies on scaffolding collaboration. SituLearn has reached technical maturity to the point of being available to educators. When designing an activity, educators provide valuable details of the context that can be used for further evaluation both across different context and in longitudinal experiments (evaluating the progress of players throughout their academic career). So far, we have built on the Situlearn model with the results of our research. It is clear that educators must be assisted in the creation of collaborative games, the extent of what is possible still seems subject to research of the CSCL community itself (as illustrates the systematic review of serious games for collaborative learning by C. Wang and Huang (2021)). An interesting perspective from our point of view, would be the integration of SPART into a SituLearn field trip. Such an integration seems promising primarily due to the augmentation SPART provides for static surfaces, a fact illustrated by the double integration of SPART both in the PAC Framework and the extended SituLearn model. Another perspective is the use of the map in SituLearn as visualization of the game achievements and structure. Game elements such as answers to questions, photos and voice records exist in the context of the situated game. By visualizing samples and information on the map, information can be more easily integrated into a mental model, directly assisted by a visual representation of the reality in the field. Supporting game elements representation also supports the mental representation built up by the pedagogical content

of the activity. Furthermore, the field trip can be replayed in the classroom purely with a map and SPART. A virtual field trip for instance can consist in a virtual representation of the group on screen with the same resources as in the field (time for example), the same orchestration possibilities as mentioned previously, and simulated speed and obstacles encountered in the field for their virtual avatars. We hypothesize that such a virtual field trip is likely to foster similar reinforcement patterns as dedicated map supported mindwalks described in the previous chapter.

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PART VI

Appendices

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TECHNOLOGY ASSESSMENT

The following sections detail the overall evaluation of technologies in chapter 8 in part III, table 8.2.

A.1 Gravity Based Technologies

Since the dominating force direction of gravity on earth points to the center of the earth, the only viable localization technique is fingerprinting: the creation of artificial gravity fields is infeasible due to the mass required. However, there are multiple sensors that can measure an object's attraction to the earth's surface.

A.1.1 Piezo-Electric Sensor Grids

The piezo-electric effect is a redistribution of electric charges in crystalline materials in response to physical stress. The effect is a reversible process and piezo-electric elements are widely used both as transducers and emitters. Rosenberg et al. have demonstrated the

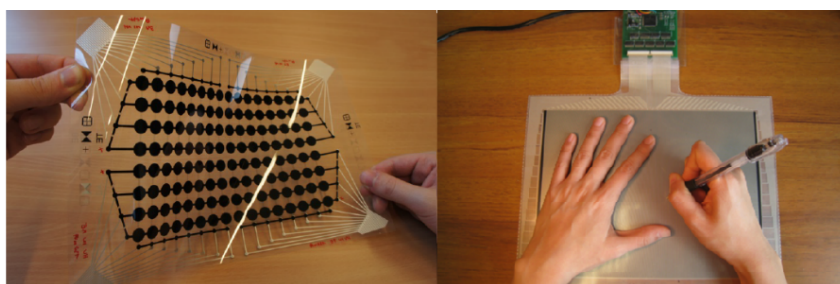


Figure A.1: right: Bendable prototype for pyzoflex, left: unmousepad

feasibility of bendable piezo-electric sensor grids (Rosenberg and Perlin 2009). However, their solution Unmousepad is not foldable (figure A.1). Manufacturing a foldable version for a geographic map is also outside the scope of this project, since it would require one grid per map section. Rendl et al. have created a similar project, called Pyzoflex, based on a piezo-electric grid that uses functional ink. The circuits can simply be printed on the bendable support (Rendl *et al.* 2012). The framerate for both projects is given at 100 fps.

However, the technology requires ferro-electric polymers to work and special printers. It is thus unfit for the production in educational or DIY settings.

Table A.1: Evaluation of piezo-electric grids

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Piezo-electric sensor grid	1.5	1.5	1	1	0.5	1	0	1.5	0

A.1.2 Mechanic Switch Grids

Using typical small factor switches, a grid of switches could locate multiple smartphones in a fixed size area. Contrary to capacitive touch pads or piezo-electric sensor grids, this solution also requires one switch per square centimeter. For an A3 surface, this results in 1176 switches which is not feasible at a reasonable cost or time. Additionally, connecting each of those switches to a microcontroller makes this solution very complicated to set up. Another problem with switch grids originates from the force required to push down the underlying buttons. Indeed, larger smartphones might not activate the buttons because the resistive force of a higher number of switches is higher than the gravitational force.

Table A.2: Evaluation of switch grids

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Switch grids	1	1.5	1	1	0.5	0	0	0	0

A.1.3 Analog Potentiometers

Potentiometers are used widely in input devices to set a continuous value. A potentiometer consists of a resistive material and a sliding contact. Holman et al. have designed a low-cost, DIY linear potentiometer, called TactileTape, where the wiper is formed by touching a three-layer construct consisting of a resistive, conductive and isolating layer.

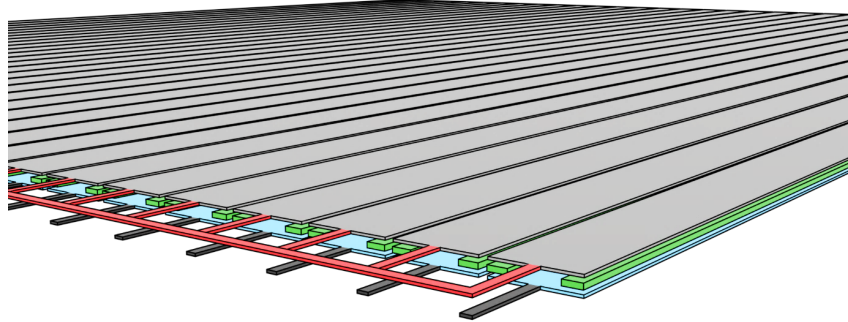


Figure A.2: TactileTape sensors in an array form a location sensitive surface. Black: Ground, Red: Data

The pressure of the finger closes the circuit and the resistance value corresponds to the distance (Holman and Vertegaal 2011). While such a sensor can only measure distance, using an array of sensors could detect the presence of an object on a 2D plane (see figure A.2).

Figure A.2 illustrates individual sensor structure and relative layout: each sensor consists of a conductive layer (blue), an isolating layer (green) and a conductive layer (gray). When an object closes the gap between resistive and conductive layer, the sensor in question has a different resistance than the others. The sensor itself and its value correspond to the position of an object. Two spherical small tips can be attached to springs on the bottom of a smartphone so that when one is situated on the isolating layer, the other triggers the closest sensor. For an accuracy of 1 cm on a A3 sheet, 30 sensors are required. The layout in figure A.2 can be simplified with one continuous conductive surface and only one isolating layer between two neighboring sensors. Resistive materials like carbon paper or velostat should work. Thin foam for the isolating stripes is a good option. Copper tape is an appropriate material for the conductive layer. While this technical solution seems feasible, it still remains to be tested how well a smartphone can close the contacts. In terms of material, the solution is both affordable and DIY compatible. Multiple devices can be detected at once and the system is bendable as well as foldable. Reading values on microcontrollers can be done at high frequency, even on multiplexers (necessary for managing 30 sensors). The only drawback to potentiometers is, that multiple devices cannot be distinguished.

Table A.3: Evaluation of a potentiometer based concept

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Analog Potentiometers	1	1.5	1	1	1	1.5	1	0	0

A.2 Electromagnetic Wave Based Technologies

The use of electromagnetic (EM) waves is not without problems, since objects reflect waves and the reflected waves travel over a longer distance than the actual distance between emitter and receiver. Moreover, waves can get absorbed by material and wave strength varies with environmental properties such as temperature and humidity. Nevertheless, we explore the possible combinations of electromagnetic waves with the three main localization techniques.

A.2.1 Optic Dead Reckoning

Modern computer mice use an optical sensor to detect their direction and speed. Accuracy is heavily impacted by surface homogeneity and the rotational disturbance of the mouse. The latter refers to the fact that mice do not take into account their rotation, thus impacting the accuracy of a potential positioning system. Sekimori et Miyazaki have successfully used multiple mouse sensors to account for this problem (Sekimori and F. Miyazaki 2007). However, even with multiple mouse sensors, the position still had to be corrected by an external camera system. Authors of studies on the usage of computer mice as positioning devices such as Ka-Ping Yee, who used computer mice to conduct experiments of peephole display implementation, have abandoned the initial approach of using optical mice in favor of absolute positioning systems (Yee 2003). Another issue with computer mice as components for positioning systems is the problem that position cannot be tracked beyond any lifting of the device, which may naturally occur when used on uneven ground (such as a map). Computer mice initially seemed like a cheap and robust way to achieve accurate positioning. However, increasing errors over distance would require SPART users to regularly restart at a known position. Further issues with varying surface and rotation make this approach non-viable for the use as a localization technology. Since the main requirement of accuracy is not met, the solution receives a

total score of 0.

Table A.4: Evaluation of a computer mouse based concept

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Mouse-based localization	0	1.5	1.5	1	0	1.5	0.5	1.5	0

A.2.2 GPS

Synchronized multilateration uses the time a wave needs to reach receivers installed at different, known points in space. Similarly, multiple emitters at known points can emit signals with information about their position and time of emission for a single receiver to locate its position. A precondition for such a system to work are perfectly synchronized emitters at the reference points. GPS is a prominent use case of this technique where multiple satellites emit exact information about their location and time of emission. Due to the very fast propagation speed, satellites use a network of atomic clocks to provide exact time information (Kenneth R Jr 1991). Information about the time the GPS signal is encoded within the signal. Typical outdoor accuracy of GPS is in the range of 5 m. Different versions of GPS (such as dGPS) use additional ground emitters to increase accuracy to 1 m. With the development of Galileo (EU) and Glonass (Russia), smartphones nowadays support the use of all three of them concurrently under the standard classification of GNSS-2 (2018) with an accuracy of about 1 m in good conditions (*Superaccurate GPS Chips Coming to Smartphones in 2018 - IEEE Spectrum 2023*). Accuracy can vary whenever the GPS signal is subject to multipath effects (high buildings in cities, forests or trees may reflect the signal). If GPS was to become accurate enough for our project, a possible setup would consist of an external gps module as a reference point connected to a bluetooth emitter communicating the reference position (at the edge of the map) to the smartphone, aware of its own position). Currently, GPS does not provide sufficient accuracy for the use as a high resolution 2D positioning system. In terms of fluidity, the refresh rate is limited to 1Hz. Due to reflection issues, its use might also be restrained to environments without obstacles. As such, GPS is not a suitable solution.

Table A.5: Evaluation of a computer mouse based concept

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
GPS	0	0	1.5	1	0.5	1	1	1.5	0

A.2.3 Wifi Strength

Geometric location systems based on Wifi traditionally used information about the strength of the signal ("Received Signal Strength Indicator", RSSI) as pseudo distance to the receiver. Zhu and Feng have developed an algorithm with an average deviation of 80 cm (Zhu and Feng 2013). 1 m accuracy can be achieved with Wifi RTT, a Time of flight solution available since Android 9 (inpaint-hardware.com 2018). However, since meter-range localization is a sensible issue of privacy, this technology needs explicit user agreement whenever used. Furthermore, since Android 8, the scan frequency has been decreased to 4 scans every 2 minutes. Both fluidity and accuracy make this approach unfeasible for high-precision 2D positioning.

Table A.6: Evaluation of Wifi signal strength

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
WIFI Fingerprinting	0	0	1.5	1	0.5	1	1	1.5	0

A.2.4 Wifi Time Of Flight

As with other EM wave based systems such as GPS, a major challenge is synchronization of clocks and time resolution. Schauer *et al.* (2013) achieved an accuracy of 1.4 meters in accuracy by using ICMP time packet signatures in a WIFI round-trip time of flight approach to avoid synchronization of clocks between emitter and receiver. Roundtrips consist of sending a signal to a remote receiver which immediately upon arrival will send a reply to the emitter. It is obvious that the delay between receiving the signal at the receiver and sending it back is non-deterministic and introduces delays (network congestion, error

delay due to correction of corrupted packets etc.). If the approach had a better accuracy, it would be both affordable and robust. Accuracy may be improved by designing a custom set of emitter and receiver implementing a lower level timing protocol: ICMP uses the system's clock before handing the request over to its network card (inducing further imprecisions). Similar limitations apply to protocols like Bluetooth.

Table A.7: Evaluation of Wifi time of flight approaches

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
WIFI ToF	0	1.5	1.5	1	1	1.5	1.5	1.5	0

A.2.5 EM Doppler Effect

The difficulties of measuring the Doppler Effect in acoustic scenarios also apply to electromagnetic waves. Due to the high speed of propagation, a high sample frequency is required. Peng and C. Li (2019) tested a 5,8 GHz Doppler radar and achieved an error of multiple centimeters in their scenario of object detection. The high sampling frequency and insufficient accuracy makes this approach unsuitable for our context. The missing availability of suitable parts (due to the wave type being microwaves) means that such localization systems are neither affordable nor compatible with a DIY approach.

Table A.8: Evaluation of the electromagnetic Doppler effect

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
EM-Doppler effect	0	1.5	1.5	1	1	0	0	1.5	0

A.2.6 Interferometry

Interferometry is a class of techniques that are based on the superposition principle. Typically, a beam of electromagnetic waves travels through a beam splitter. This creates

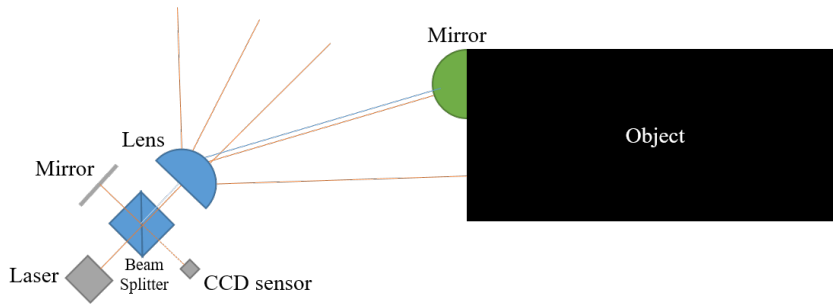


Figure A.3: Interferometer design for multilateration

two separate electromagnetic waves of the same wavelength which are redirected. One wave is reflected back from a mirror placed on the reference object and is recombined with the second wave. Both are now overlaid and the offset of both waves creates fringes which can be interpreted as the difference in distance. Depending on the wavelength of the emitted beam, the precision varies. Interferometers using visible light can measure distance differences in the magnitude of nanometers. The distance between the fringes for a 1mm variation in length with a typical 650 nm red light laser would be approximately 325 μm . The fringes could be digitized with Charge Coupled Device sensors (as used in flatbed scanners). Line CCD sensors consist of an array of linearly arranged photo sensitive elements. The mirror of the moving object has to be aligned at all times with the laser beam introducing additional complexity. Indeed, the setup would require either motors to align the mirrors on the object to reflect the light beam back to the interferometer, or a perfect cylindrical mirror attached to the object in order to always reflect some light back to the interferometer (see figure A.3). Using this approach, the design of a multilateration laser interferometer is theoretically possible.

A commercial CDD TCD1304 has a clock rate of 4 Mhz and 3648 pixels but requires four clock cycles to retrieve data from one pixel. The complete array can thus be retrieved at 274Hz. These specifications are insufficient for use with visible light. Fringe patterns are cyclic: whenever the distance difference exceeds one wavelength, the pattern repeats. Thus, to capture an object at a speed of 1cm/s, the sensor would be able to accurately capture 16000 cycles per second. To accurately sample a 16kHz signal, a 32000 samples (Nyquist rate) would have to be captured per second. To remedy this problem, longer wavelengths outside the visible spectrum would have to be used, which is not feasible with DIY hardware (mirrors, beamsplitters etc.) (-Affordability, -DIY). (but as described only viable for slow movements). In turn, finding parts like beam splitters and cylindrical

Table A.9: Evaluation of interferometry

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Interferometer multilateration	1.5	0	1.5	1	0	0	0.5	0	0

mirrors is difficult (-affordability). Another challenge with this setup is the signal to noise ratio (-robustness): Ambient radiation is present in outside conditions and a line laser's band reduces strength per surface of the emitted light. The fraction of the light that hits the cylindrical mirror is only a low percentage of the emitted light and gets further spread out. Pulsing the light would further increase the need for higher sampling frequency to avoid skipping wave cycles on object movement.

A very practical issue with such a setup is that it would require the object to always be perfectly aligned with the reference plane which may not be the case in outside conditions with paper maps (-robustness). Last but not least, two such devices would be required to obtain two lengths from which the position could be calculated.

A.2.7 IR Modulation

IR refers to electromagnetic waves emitted in the infrared spectrum. Raharijaona *et al.* (2017) have shown the successful use of flickering IR diodes to accurately and timely localize a robot. The system is based on two emitter diodes mounted at a height of two meters and a receiver system on the robot. The achieved accuracy of this design is 1cm. The system has not been tested in outside conditions and it is questionable that under influence of sunlight the accuracy can be maintained. Another aspect would be the implementation of the approach in a mobile setting. If the principle was to be implemented through a compact base station, the sensors would have to be situated in a frame around the device to locate and powered by the mobile device. Fluidity is given with 33Hz.

A.2.8 Lighthouse Tracking

Systems like the HTC Vive Virtual Reality headset use beacons that contain rotating infrared lasers and communication modules to communicate the rotation position. Two lighthouse beacons are sufficient to provide information about position in 3D space. The

Table A.10: Evaluation of IR modulation

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
IR modulation	1	1.5	1.5	0	0	1	0.5	1	0

sub-millimeter accuracy was confirmed by Sitole *et al.* (2020) who tested the solution with an industrial robot arm and reported errors below one millimeter. Powering mobile lighthouse beacons and making them robust (rotating parts) all while remaining DIY compatible, present multiple challenges that make this solution inadequate for our use case. Another limitation to the use of lighthouse tracking is the direct visual contact required to make this solution work. This also makes this solution incompatible with multiple devices (one device can interrupt visual contact with another one)

Table A.11: Evaluation of lighthouse tracking systems

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Lighthouse tracking	1.5	1.5	1.5	0	0	0	0	0	0

A.2.9 Light Triangulation

Light triangulation is typically used in 3D scanners. A laser beam is projected on a surface and an image sensor is mounted at a fixed angle relative to the laser. The image sensor captures the laser point on different positions depending on its distance to the aperture. The accuracy depends on the resolution of the image but can achieve accuracy above 1mm. Using a band of light instead of a single beam, the 2D shadow of an entire object can be captured without any moving parts. In order to cover an A3 sheet, the optics of a laser have to cover 30 cm if used on the short side. Optics for lasers allow for lines as large as 120° which requires the apparatus to be positioned at about 5cm to the sheet. The sensor itself has to be a high resolution CMOS-sensor/camera (see figure A.4).

Scavella (2020) have managed to create a functional 3D scanner with a standard

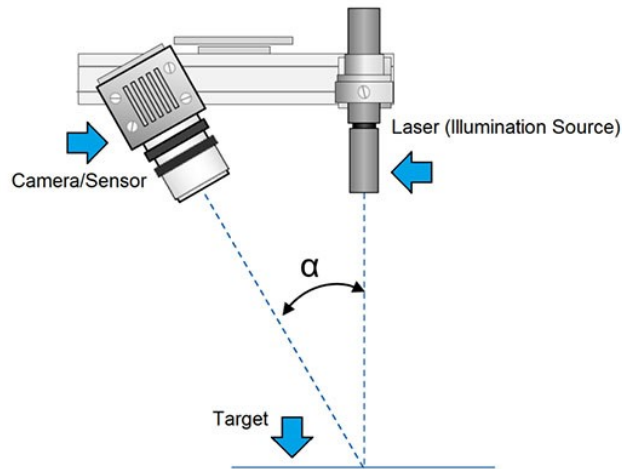


Figure A.4: Illustration of the working principle of light triangulation. Image source: [Scantech](#)

Raspberry Pi Camera at 5 Megapixel. Accuracy of this project is on a sub-centimeter level. However, with increasing distance, accuracy will decrease since for a given delta in distance, the corresponding delta on the sensor becomes smaller and with a fixed resolution will result in less pixel per distance delta. Material cost for a mobile version is estimated at around 10€ (line laser) + 20 € (battery shield and battery) + 20 € (raspberry w zero) + 15 € (raspberry camera) = 65 €. Fluidity depends on the camera sensor (typically 30 fps). The surface has to be perfectly flat for this approach to work. Since only the shadow from one side is recorded, more than two devices of equal size will shadow a potential third device (-multi-device). The approach promises fluidity of 30 Hz. While accuracy cannot

Table A.12: Evaluation of light triangulation techniques

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Light Triangulation	1	1.5	1	1	1	1	1	0.5	8

be estimated beforehand, an average error of 1 cm seems feasible. A potential prototype seems sufficiently mobile and without moving parts sufficiently robust. Laser light being of high intensity, discrimination against environmental influences such as sunlight does not seem an issue. Two devices of equal size can be located when at distance of the sensor and not shadowing each other. Using complementary computer vision, a second device

may be located even when shadowed.

A.2.10 LIDAR

Lidar refers to light detection and ranging and uses time of flight of a laser beam to measure a distance. This limits its accuracy to multiple centimeters in commercially available modules due to the very short time of flight requiring costly sensors to achieve higher than 5 cm accuracy (DIYEngineers 2022). Additionally, any particle such as dust or rain may impact sensor accuracy as well as heat or humidity (Measure 2023). Available LIDAR sensors do not provide required accuracy for this use case. Robustness is another caveat of LIDAR (as well as any other light based distance measuring method).

Table A.13: Evaluation of commercial LIDAR modules

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
LIDAR	0	1.5	1.5	1	0	0.5	1	1	0

A.2.11 IR Angle of Arrival

Arbula and Ljubic (2020) have successfully tested a system that uses the angle of arrival of infrared light. Their system provides an accuracy of 7 cm. This is however insufficient for

Table A.14: Evaluation of IR angle of arrival techniques

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
IR Angle of Arrival	0.5	1.5	1.5	0.5	0.5	1	0.5	1	7

our use case (-accuracy). While the system itself may not be interesting, IR diodes have the property of decreasing sensitivity with increasing angle. It might thus be possible to increase accuracy by adding more emitters and receiver diodes to a local setup. While the work of Arbula et al. cannot be directly applied to our context, the underlying principle of modulated IR angle of arrival has the potential to provide sufficient accuracy.

A.2.12 IR Distance Sensors

IR distance sensors work by measuring the intensity of a reflected infrared light beam. Commercially available sensors such as the Sharp GP2Y0A21YK0F have an accuracy given as percentage of the measured distance (10%). This means that for a distance of 10 cm the accuracy is 1 cm but any further distance measurement is higher than a centimeter (which is not suitable for this use case). Other limitations are the material of the reflected surface and outside weather conditions such as direct sunlight (SHARP 2023). Distance sensors can be mounted on a motor or deployed in an array at one side of the surface on which the position of a device is to be determined. For this approach to work appropriately, sensor accuracy and robustness are preliminary. IR distance sensors do currently not provide the required accuracy nor robustness.

Table A.15: Evaluation of IR angle of arrival techniques

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
IR distance sensors	0	1.5	1.5	1	0	1	1	1	0

A.2.13 Visual Tracking

Visual tracking solutions depend on the device's camera resolution. There is no external hardware involved other than a marker on the map. Markerless visual tracking is a computational intensive approach. So much so that Google's ARCore framework providing such functionality is only supported on a handful of high-end devices (such as Samsung S9 and above (*Overview of ARCore and Supported Development Environments* 2022)). There are libraries for marker based tracking and Basiratzadeh *et al.* (2019) successfully managed to detect multiple markers and reliably measure the distance between them. Using fiducial markers, their approach requires hardware as found in devices such as Samsung S5: 2 GB RAM, 2,4 GHz Quadcore. The framerate varies with the camera specifications of the device but can be considered at least 30 fps. As such, marker based tracking presents the possibility of localizing a marker in space. Babinec *et al.* have successfully used this approach with an accuracy of 1.5 cm for cameras with a camera sensor resolution of 0,44 megapixels. With modern smartphone cameras with resolutions up to 100 times more

(e.g. Samsung S21) accuracy should increase accordingly. The authors noticed that with increasing angle from fiducial markers relative to the camera, accuracy decreased. Additionally, obstacles between tracked and tracking smartphone may interrupt the positioning process. The tracking smartphone would thus require some kind of supporting structure. The fiducial marker itself would take up some screen space, decreasing available screen space to augment the underlying surface. While accuracy and fluidity may be possible with marker based tracking, the robustness of the method depends on angle and light conditions. The fact that a second smartphone is required impacts affordability. It seems possible to track more than one marker at once, which makes the method suitable for multi-device tracking.

Table A.16: Evaluation of camera based tracking techniques

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Fiducial marker tracking	1	1.5	1	1	0.5	0.5	1	1	7.5

A.2.14 CIS Shadowing

Contact image sensors are linear arrays of detectors used in flatbed scanners. By attaching such a sensor to one side of a surface and adding light diodes to the opposing side, a device can be located by sequentially turning the LEDs on and off, essentially creating different

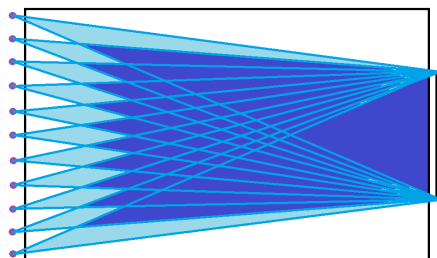


Figure A.5: Illustration of CIS shadowing. Left: Diodes in an array. Right: CIS line sensor. Image source: [hackaday](https://hackaday.com)

types of shadows on the sensor from which the position of the device can be deduced (figure A.5).

The approach was tested as a touch screen solution. This means that it was used with small objects such as a finger and it is not clear if a larger object such as a smartphone would yield similarly accurate results. The area covered isn't rectangular either, leaving blind spots in detection. However, as it is a light based solutions, this approach is sensitive to outside influence such as sunlight.

Table A.17: Evaluation of CIS shadowing

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
CIS shadowing	1.5	1.5	0.5	0.5	0.5	1	1	0.5	7

A.2.15 UWB

Ultra Wide Band is a technology embedded in recent smartphones (Apple Iphone Google Pixel 6 and 7 Pro, Samsung S21 Ultra and above (*Ultra-Wideband (UWB) Communication* 2023)). Using pulses at a nano-second interval across a 500 Mhz bandwidth, this solution can achieve 10 cm accuracy and a refresh frequency of 30 Hz (Mearian 2019). While there is no issue with fluidity compared to Bluetooth and Wifi, accuracy still falls short of our requirements. It is thus unfit for the use case of an ultrafine positioning technique.

Table A.18: Evaluation of the Ultra Wide Band technology

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
UWB	0	1.5	1.5	1	0.5	1	0	1.5	0

A.2.16 NFC

NFC is an ultra-short range transmission technology based on RFID. The technology allows wireless energy transfers. This allows for the use of data stored on NFC-tags which

get energized when a NFC device is near and allows to wirelessly read the data on the tag (STMicroElectronics 2023). In theory, a grid of NFC tags attached to the surface on which a device is to be located, enables such an NFC device to determine its position by simply reading the underlying tag, given that the tag has its physical position saved to its storage (see figure A.6).

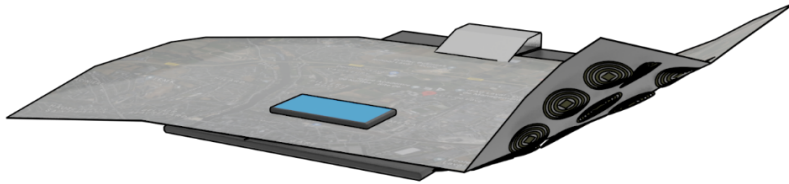


Figure A.6: Illustration for the use of NFC tags as localization beacons

However, the antenna range varies and may allow to read a tag at a distance of up to 10 cm. This means that reliably reading the closest tag becomes impossible. Furthermore, Android limits the reading frequency to 20 Hz. This makes it easy to “miss” a tag while sliding the device over the surface, which is problematic if the tags have to be widely spaced. Finally, scalability is another issue because, if every square centimeter has to be covered by an NFC tag, 1200 tags would be required for an A3 sheet.

Table A.19: Evaluation of NFC fingerprinting

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
NFC Fingerprinting	0	0	1.5	1	1	0	1	1.5	0

A.3 Electric Force Based Technologies

Electric fields have similar properties as magnetic fields. Electric fields exert forces on charged particles, causing their movement along field lines, while magnetic fields exert forces on moving charged particles, resulting in circular or helical motion. The superposition principle applies to both field types. Thus, the previously described magnetic localization techniques can be applied to electric fields as well. Meanwhile, there are no

static electric materials that correspond to static magnets for magnetic fields. Thus, electric fields have to be maintained by keeping electric charges on capacitor plates which requires a power source and additional wiring. Consequently, static electric field positioning technologies (dead reckoning or geometric techniques) are too complex (-DIY) for our use case. In turn, the capacitive coupling effect occurring in electric fields can and is exploited in fingerprinting localization techniques discussed in the following subsections.

A.3.1 Capacitive Touch

Capacitive touch screens are based on the principle of capacitive coupling. When a conductor approaches a surface under voltage, current is drawn from the surface. In projected capacitance, a grid of electrodes provides information about where the conductor is located on the surface. Touch pads can be produced with any type of conductive material such as copper or conductive ink. Pourjafarian *et al.* (2019) have developed a kit to create such touch pads. While accuracy can be within 2 mm and fluidity at 30 Hz, according to Pourjafarian et al., the number of electrodes and thus input pins required is linearly proportional to the size of the surface. The authors recommend electrodes every 6mm. In order to cover an A3 surface, 50 output pins and 70 input pins would be required. A typical multiplexer such as the CD74HC4067 has 16 channels but takes up 4 digital pins for selecting the output channel. Thus, 10 multiplexers would be required. Connecting and housing those multiplexers, external power supply and microcontroller makes a potential prototype cumbersome, though not practical to implement. To distinguish multiple devices on the same grid, the devices must have multiple, distinguishable capacitive contact points.

Table A.20: Evaluation of Capacitance technology

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Projected Capacitance	1.5	1.5	0	1	0.5	1	0.5	1	0

A.3.2 Electric field tomography

Zhang et al. propose a DIY approach for the use of electric field tomography. Their approach uses a conductive medium in which an electric field is sequentially created by multiple electrodes attached to the material borders (see figure A.20). Introducing a conductive material (such as human skin) to the field results in capacitive coupling and a small current being drawn from the field. The resulting voltage drop can be measured between the electrodes. The method works on a multitude of easily available materials such as velostat or 3D printing filament, coatings etc. with velostat working best due to its homogeneity. Since capacitive coupling does not require direct contact, a sheet of paper can be put on top of the conductive medium. The electric field is an oscillating AC signal generated from an AD5930 chip. A set of multiplexers send the signal to the electrodes. The measuring electrodes are connected to a preamplifier before being sent to a custom board built around a Cortex M4 Microcontroller. The authors report a total price off 7 \$ and a power consumption of 120 mAh in normal operation which in conjunction with a standard 18650 LiPo battery equals to an autonomy of around 18h of continuous operation (+mobility). It is unclear how a smartphone would influence those fields, but it would

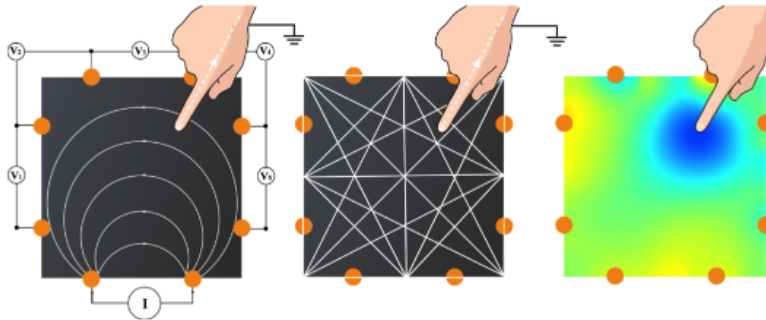


Figure A.7: Zhang et al.'s DIY electric field tomography approach. Illustration by Zhang et al.

require some attached conductive material to provoke a detection in Zhang's system. If it was to be used in an educational context, the developed board would have to be available for purchasing (which is not the case as of this writing).

Table A.21: Evaluation of electric field tomography

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Electric field tomography	1.5	1.5	1	1.5	1	0	0.5	1	0

A.4 Magnetic Force Based Technologies

Magnet based technologies can make use of the internal magnetometer of smartphones and therefore seem particularly promising for a highly integrated solution. However, magnetic fields and ferromagnetic materials that might impact the artificial field(s) are common and difficult to prevent (-robustness). We discuss fields from static magnets only since electromagnets that create measurable static fields have a high power consumption incompatible with our mobility requirement. An exception are weak pulsed magnetic fields that will be discussed.

A.4.1 Magnetic Dead Reckoning

While there is no evidence from keyword research for studies on a magnetic dead reckoning system, its concept is trivial. Figure A.8 illustrates the idea in a simplified one dimensional context. Two analog Hall sensors s1 and s2 move along an axis above magnets oriented in alternating direction. At t_0 S1 detects a vector and S2 does not. Transition from $t=0$

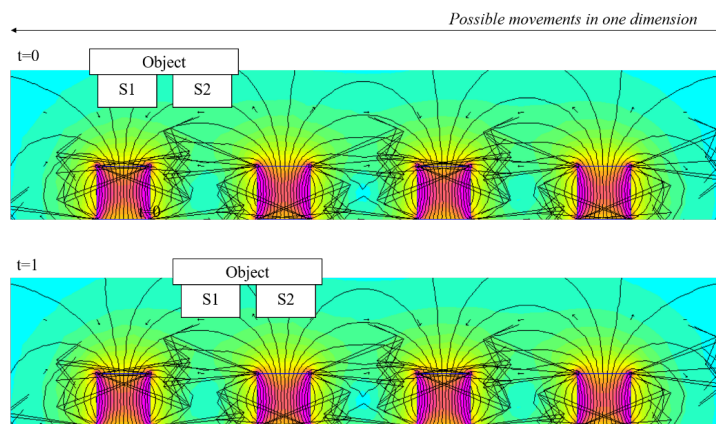


Figure A.8: Illustration of magnetic dead reckoning in one dimension

to $t=1$ results in a monotonic increase of values in both S1 and S2. Since the movement is cyclic, two sensors are required to detect when monotonic decrease equals a move to the right (beyond the second magnet). Such a cyclic pattern can also be used on a 2D plane with two more sensors to detect lateral movement. This approach has the typical shortcomings of dead reckoning techniques, notably the problem of relative measurements from one initial known point of reference, which means that once the object is lifted and ascended back on the magnet-covered surface, it has to be reinitialized (-robustness). In return, the use of a grid eliminates the problem of a cumulating error, while the accuracy and fluidity with hall effect sensors should be available. The possible surface has no limit, but costs are proportional to the surface. Using multiple devices is possible. The sensor array can be attached to the phone.

Table A.22: Evaluation of a magnetic grid dead reckoning

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Magnet dead reckoning	1.5	1.5	1.5	1.5	0.5	1	1	1.5	10.5

A.4.2 Magnetic Beacons

The internal magnetometer of smartphones can measure magnetic field strength in three directions using the Hall effect. A heterogeneous magnetic field might thus provide a unique field vector per position. The shortcomings of magnets as beacons are their rapidly declining field strength over distance ($1/\text{distance}^2$). A single magnet is therefore insufficient to cover the entire surface. Another problem is oversaturation when the sensor is too close to a magnet. On usage of a potential system, the internal smartphone's magnetometer has to be calibrated to account for surrounding inferences (such as the earth's magnetic field). If those problems can be overcome, the technology can provide an affordable 2D positioning system with the required accuracy and fluidity. Static magnets' high (even though spatially limited) accuracy and fluidity have been notably used in the field of capsule endoscopy where Guo and Shao (2021) report a 1 mm accuracy in a 20x20x20 cm volume. The approach has also been successfully used to use static magnets as input devices for smartwatches by Abe *et al.* (2016), using the internal magnetometer to locate

a magnet around the smartwatch. In a circle of 15 cm radius around the smartwatch, errors ranged from 3 to 11 mm.

Table A.23: Evaluation of a magnetic beacons

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Static magnetic beacons	1.5	1	1	1.5	1	1.5	1.5	1.5	10.5

A.4.3 Pulsed Magnetic Fields

Pulsed magnetic field tracking relies on multiple coils arranged in different directions, referred to as the transmitter. When the coils are sequentially powered, magnetic fields are created in the direction the individual coils face. The magnetic field can be measured by magnet sensors. Multiple sensors can determine their orientation and position within the fields with high accuracy (1 mm) and fluidity (100 Hz) in good conditions (Franz *et al.* 2014). A major issue with using magnetic fields for localization is the decrease in field strength over distance. Hence, either strong magnetic fields are required to cover the required distance, or high sensitivity sensors have to be deployed. Typical Hall effect sensors like magnetometers as used in smartphones do not convene for such a system. Sensors with higher magnetic and temporal precision typically used in such systems are magneto resistive sensors. Contrary to Hall effect sensors, which output a voltage proportional to the field strength, magneto resistive sensors output a current induced by a changing magnetic field. This requires additional electronic circuits to transform the current into a voltage that can be read by a conventional microcontroller (-DIY). Software wise, signal processing algorithms are required to identify the signal within the ambient magnet noise. Ferromagnetic objects or magnets distort the fields and lead to errors in readings (-robustness). A connection between transmitter and sensors is required to synchronize the magnetic fields and sensor readings at 1Hz (-fluidity) to reduce power consumption. However, a battery pack of four AA batteries could not power the setup of Roetenberg *et al.* (2007) longer than 20 minutes (-mobility). Affordable commercial electromagnetic tracking devices currently only are available in the form of the discontinued game controller Razer Hydra. The controller was developed by Sixsense Entertainment and released

in 2011 for 60 \$. It tracks two controller's position and rotation with an accuracy of 1 mm and 1°. A base station emits magnetic field pulses at a magnitude of 1-6 μT through 3 coils in 3 dimensions. The controller measures the field strength in three dimensions and thus can determine its rotation and position within the field. The controllers are connected to and powered from the base station. While it would be theoretically possible to detach the controller circuit and power it from a smartphone all while getting the position data, the system would also require an external base station, leading to maximum complexity of external components, questionable reparability and an effort in terms of modifying an existing product beyond the abilities of unspecialized personnel (-DIY). Building such a system with available components requires a high complexity in assembly and soldering components. Software wise, signal processing algorithms are required to isolate the weak magnetic field measured from surrounding noise. Since the Hydra is a proprietary device, the required computational power is unknown.

Table A.24: Evaluation of weak pulsed magnetic fields

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
EM-Tracking	1.5	1.5	1	1	1	0	0	1.5	0

A.4.4 Magnetic Light House

Magnetic lighthouse tracking relies on one or multiple rotating static magnets as reference points. The angular position is known and communicated to the object. This implies the use of actuators such as stepper motors or circuitry such as rotary encoders to communicate the continuous rotation of the magnet(s). Without additional hardware attached to a smartphone, the possible angular speed depends on the smartphone's magnetometer resolution and speed (typically limited to 30 readings per second). Popek *et al.* (2017) have managed to obtain 0.1 mm accuracy but their achieved range was limited to 20cm (-range) and specialized hardware (- DIY, -Affordability, -Range). Watanabe et al. have managed to cover a larger surface (15 m²) with a spinning magnet marker and smartphone magnetometers. Accuracy did not exceed 1 cm for distance measurement and 2° for angle measurement, yielding position offsets of more than 2cm on average. The average

measurement time was 15 seconds (-fluidity) and accuracy is likely to decline when the smartphone is moved (-accuracy). While the magnet itself does not require energy, a spinning motor requires power from a source like a battery. The used motor SM-42BYG011-25 is a bipolar stepper motor rated at 12 V and 0,33 A per coil. A typical 18650 LiPo high energy density battery has a maximum capacity of 3600 mAh and rated at 3,7 V can thus provide 13,32 Wh. The motor's consumption at 3,96 W per coil could thus be powered two hours limiting mobility. Robustness is impacted by moving parts. The following evaluation is based on Watanabe's approach, since it uses a smartphone, works on the required range, is DIY compatible and affordable.

Table A.25: Evaluation of a magnetic lighthouse tracking

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Spinning Magnetic markers	0	0	1.5	0.5	0.5	1	1	1.5	0

A.5 Applied Force Based Technologies

A.5.1 Odometry

The use of wheels or a sphere to measure an object's physical motion has been the cornerstone of computer interfaces during decades. Mechanical computer mice used friction between a rubber ball and small rods to estimate relative motion of a hand resting on the mouse. In robotics, wheel motion is still used to estimate relative changes in position. The approach was sensible to small deformations in the underlying surface, small particles impacting the ball's motion and rotations.

Table A.26: Evaluation of odometry techniques

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Mechanic dead reckoning	0	1.5	1.5	1.5	0	1.5	1	1	0

A.5.2 IMU Dead Reckoning

Smartphone sensors are used for dead reckoning techniques (e.g. for map applications when GPS is temporally unavailable in environments such as tunnels). A subset of those sensors form an Inertial Measurement Unit (IMU) which generally consists of one 3D accelerometer, one 3D gyroscope and, depending on the model, a 3D magnetometer. The acceleration measured by the accelerometer can be integrated twice to obtain a delta in distance to previous coordinates. The gyroscope's and magnetometer's data can then be used to correct the occurring error to some extent. This works for short distances only as the error increases over distance even if corrected. Small movements and thus small accelerations accentuate the problem since the sensor noise to measurement ratio increases. Smartphone dead reckoning is more suited where assumptions on movements (steps) and the environment (building layout) can be used to correct the accumulating error. This is not the case on a planar surface. While the use of a solution without any external beacon or hardware seems interesting due to the low investment and ease of maintenance, the sensors of smartphones can currently not provide sufficient accuracy for the implementation of 2D position awareness. This solution therefore receives a total score of 0.

Table A.27: Evaluation of Smartphone Dead Reckoning approaches

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
IMU Dead Reckoning	0	1.5	1.5	1	0.5	1.5	1.5	1.5	0

A.5.3 Trilateration

Mechanical trilateration consists of two or more strings (or rigid sticks) attached to the device itself connecting it to two or more reference points. The length of the string (or stick) between reference point and device allows for trilateration of its position with high accuracy. Mechanical trilateration has been used in various contexts, such as spatial localization testing for internal positioning systems for articulated robot arms (Achille *et al.* 2014). Typically, string potentiometers are used to measure the length either by winding the string on a spool or, in the case of a rigid connection, by measuring rotation

of a connected gear or using a linear potentiometer directly.

While such a system might be neither very mobile (if strings are used, a mechanism to wind them up has to be physically attached to a rigid support) nor very easy to produce, it provides good accuracy and fluidity. However, string potentiometers are industrial sensors and costly (100€ and above). We have succeeded in producing a cheap (20€) string potentiometer that can be easily assembled. We thus estimate that the affordability criteria is met.

Table A.28: Evaluation of a DIY mechanic trilateration concept

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Mechanical trilateration	1.5	1.5	1	0.5	1	1	1	0.5	8

A.5.4 Triangulation

Instead of measuring the length of connected strings or sticks, one can directly measure the angle. In the case of strings, this requires sensors with minimal friction. We developed magnetic rotary encoders which proved to be appropriate, making the approach a lower cost alternative to mechanical trilateration. The angular accuracy decreases over distance and consequently the positioning error increases.

Table A.29: Evaluation of a DIY mechanic triangulation concept

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Mechanical triangulation	1	1.5	1	0.5	1	1.5	1	0.5	8

A.6 Elastic Force Based Technologies

A.6.1 Acoustic Doppler Effect

If the frequency of the emitted signal is known as well as propagation speed and the shift in frequency, the speed of the moving object can be calculated. In order to calculate a position, the result has to be integrated once (thus being by definition more robust than comparable measurements such as acceleration). Yun *et al.* (2015) have achieved a median error of 1,4 cm improving accuracy tenfold compared to an accelerometer based solution. Their setup uses a pair of speakers and a microphone attached to the moving object. Measuring the Doppler effect from signals emitted by both speakers, two distances can be deduced and the position obtained using trilateration. However, even if the error accumulates at a slower rate, a 30cm distance still results in a 5cm error which would require a user of such a system in our context to recalibrate regularly. The accuracy is also limited by the time-frequency resolution problem. It is the problem of simultaneously determining frequency shift and the timing of occurrence of a signal in a time-frequency analysis. It occurs when the signal arrives at the sensor. While reading the signal, the Doppler effect still occurs. The recorded signal is thus not a homogenous frequency. Hence, determining the frequency of the arriving signal is challenging and limits overall accuracy of the method.

Table A.30: Evaluation of the acoustic Doppler effect

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Acoustic Doppler Effect	0	1	1.5	1	1	1	1	1	0

A.6.2 Acoustic Triangulation

Acoustic Triangulation Phase shift techniques allow for the calculation of the arrival of an angle using two microphones. For triangulation in a 2D plane, at least two angles are required, increasing the amount of necessary microphones to three. This in turn requires a complementary investment in recording hardware (-Affordability). Angles of an object at 50 cm distance can be obtained at an accuracy of about 0.3° accuracy with a distance

of 5 cm between two microphones in simulations. In turn, using multiple devices with this technique is not possible due to the possibility of devices shadowing each other, reflecting emitted signals.

Table A.31: Evaluation of acoustic triangulation

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Acoustic Triangulation	1.5	1.5	1.5	1	1	0	0.5	0	0

A.6.3 Phase Shift

For high mobility, combining time of flight and phase shifting techniques can provide a distance and an angle for the use of the discussed hybrid geometric technique. Current smartphones carry multiple microphones that can be used to determine the angle of arrival of a soundwave. Using an external microcontroller listening on a microphone and emitting a signal on a speaker upon arrival of a signal from the smartphone's speaker, the distance can be estimated without a clock synchronization since microcontroller are real-time systems and the delay between arrival of the smartphone signal and emitting the second signal is constant. However, sampling microphone input in Android 10 and 11 is tied to a thread per microphone. Synchronizing and reading multiple microphone buffers is not possible due to system restrictions. Instead, either a second microcontroller with two microphones attached to the phone could be used for retrieving the angle, or the smartphone could take the role of responding with an echo signal to an external device capturing the response on two mems microphones. The I2S protocol provides the means to capture information from two microphones simultaneously. Angle accuracy in a configuration with two microphones and a 5 cm distance between two microphones at a distance of 50cm distance of an emitting object and a 20 kHz signal considering 44.1 kHz sampling frequency can be estimated at around $0,3^\circ$ in simulations. Overall performance can approach simulation values with compensation for temperature variations with a simple temperature sensor. Distance accuracy can achieve 0,1mm (Hickling and Marin 1986). This means that a hybrid solution can on paper obtain an accuracy at 50 cm distance of 0.2 cm. If filter techniques can be executed on a microcontroller, a DIY compatible,

compact and affordable system with high precision and fluidity can be achieved. In turn, the solution can only locate a single device with high accuracy if a second device is located behind the first device.

Table A.32: Evaluation of acoustic phase shift

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Phase shift & TOF Hybrid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0	0

A.6.4 Active Sonar

Sonar uses sound propagation in a medium to detect objects and their distance or relative position by analyzing the echo of an emitted sound wave. While sonar has been used on ships to detect underwater obstacles and submarines, Nandakumar *et al.* (2016) achieved centimeter accuracy with the microphones and the speaker of a smartphone for tracking objects around it. The technology uses ultrasound and works thus also in ambient noise. The surface covered corresponds to an A3 sheet. However, the algorithm is not public and thus require research on the matter. The technology seems to provide near real-time feedback. The only additional equipment required would be some kind of “finger-shaped”-stick to serve as a reference point. It seems a robust and low maintenance solution to the problem. Unfortunately, since 2016 there have been no news to the whereabouts of the project.

Table A.33: Evaluation of active sonar

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Active sonar	0.5	1	1	1.5	0.5	1.5	1.5	0.5	∞

A.6.5 Acoustic Multilateration

Similar to sonar, this technique measures the time it takes a signal to travel from emitter to receivers. However, it is not based on reflection and requires a clear line of sight. Such technology can either be synchronized (emitter and receiver communicate start and arrival time) or unsynchronized (the receiver uses the different times of arrival from multiple signals to calculate its position). Toru *et al.* (2022) managed to use this technique to create a system with millimeter accuracy to track robots. Their system uses transducers to create short sound bursts that are captured by an array of microphones attached to the robot. However, the system requires transducers to be attached to some support at a height of 2 m which is impractical for our context. Hutchison et al. have demonstrated that a planar version of Toru et al.’s system can achieve similar accuracy. The system uses four microphones in four corners of an area of 20x30 cm and a phone as source to locate. This eliminates the use of an amplifier for the transducers as in Toru et al. for signal generation. Such a system can be made portable and battery powered. Microphones can be sufficiently compact to be attached to a map or similar surface.

Table A.34: Evaluation of acoustic multilateration

	Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multidevice	Total score
Acoustic Trilateration	1	1	1	1	1	1	1	1.5	8.5

SPART-ME M HARDWARE

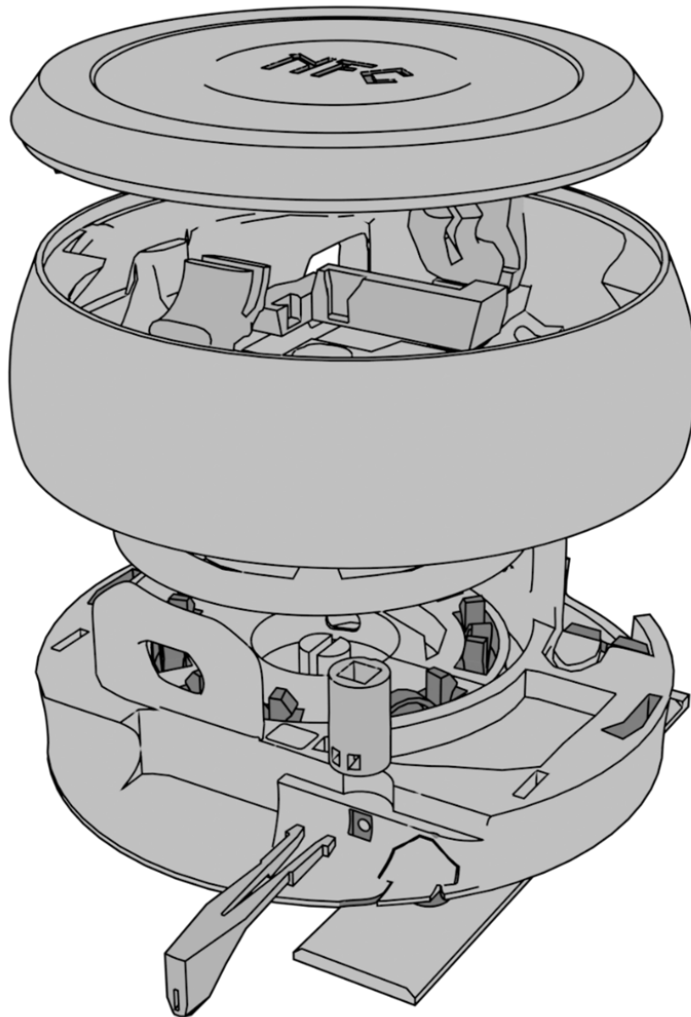


Figure B.1: Illustration of the three stage architecture of SPART-ME M with press button attachment and NFC shield

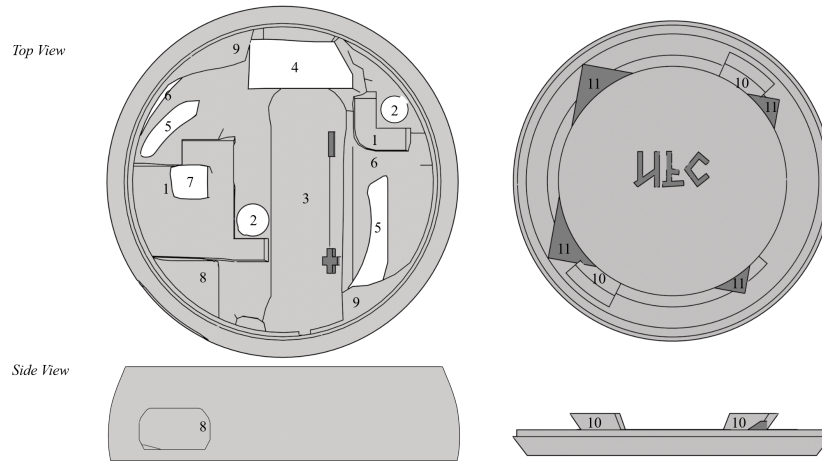


Figure B.2: SPART-ME M top shell and lid

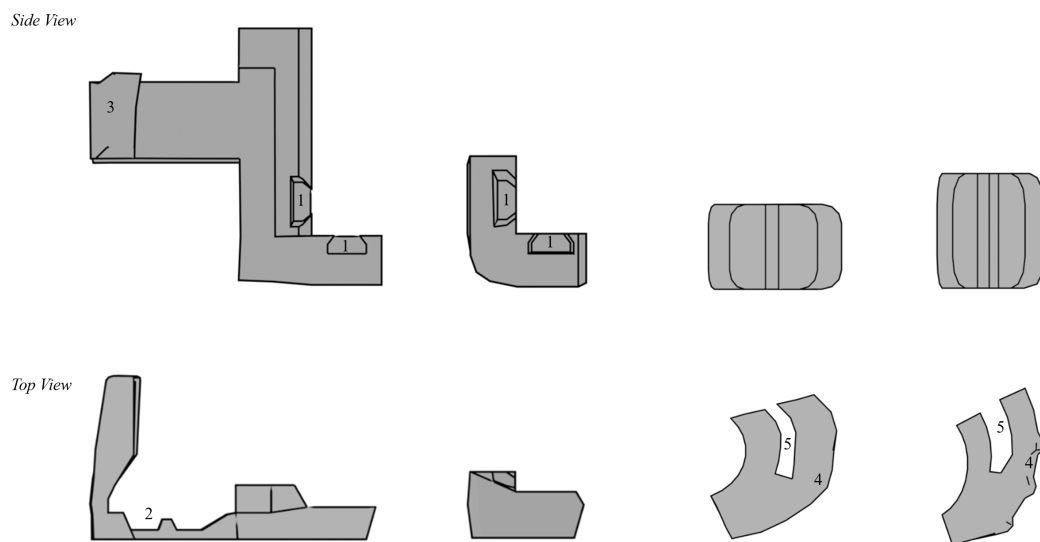


Figure B.3: SPART-ME M top parts. Left: microcontroller and sensor holdings. Right: wedges to attach the bottom to the top part

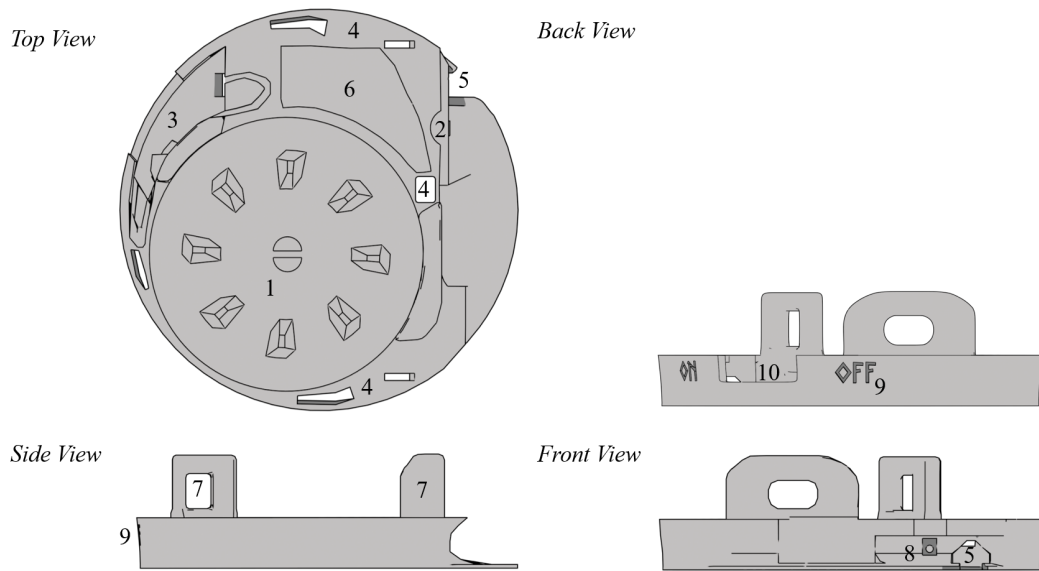


Figure B.4: SPART-ME M Bottom shell

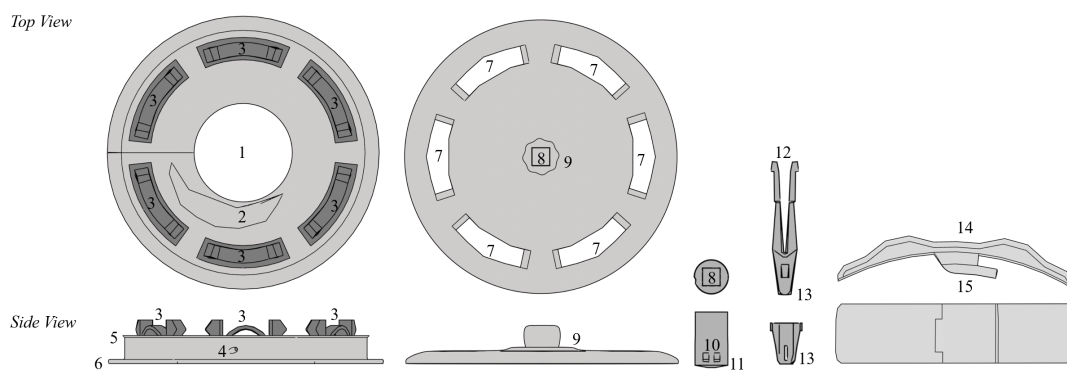


Figure B.5: SPART-ME M bottom parts: Reel, arm and power switch

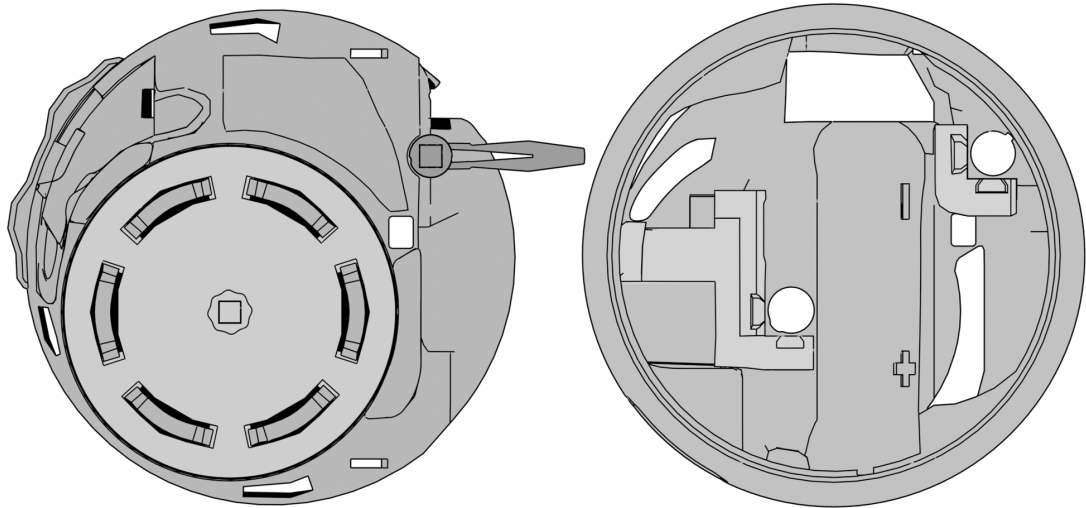


Figure B.6: SPART-ME M shells with parts. Left: Bottom part with reel, arm and power switch. Right: Top shell with microcontroller and sensor holdings

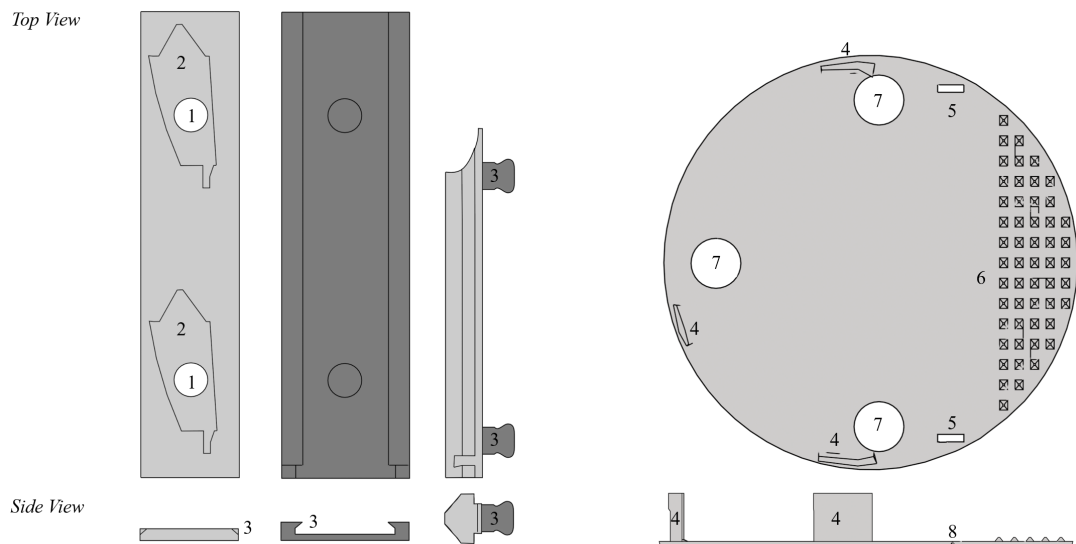


Figure B.7: SPART-ME M attachments. Left: Press button module for attachment to a surface through two holes. Right: Attachment module for paper or thin cardboard.

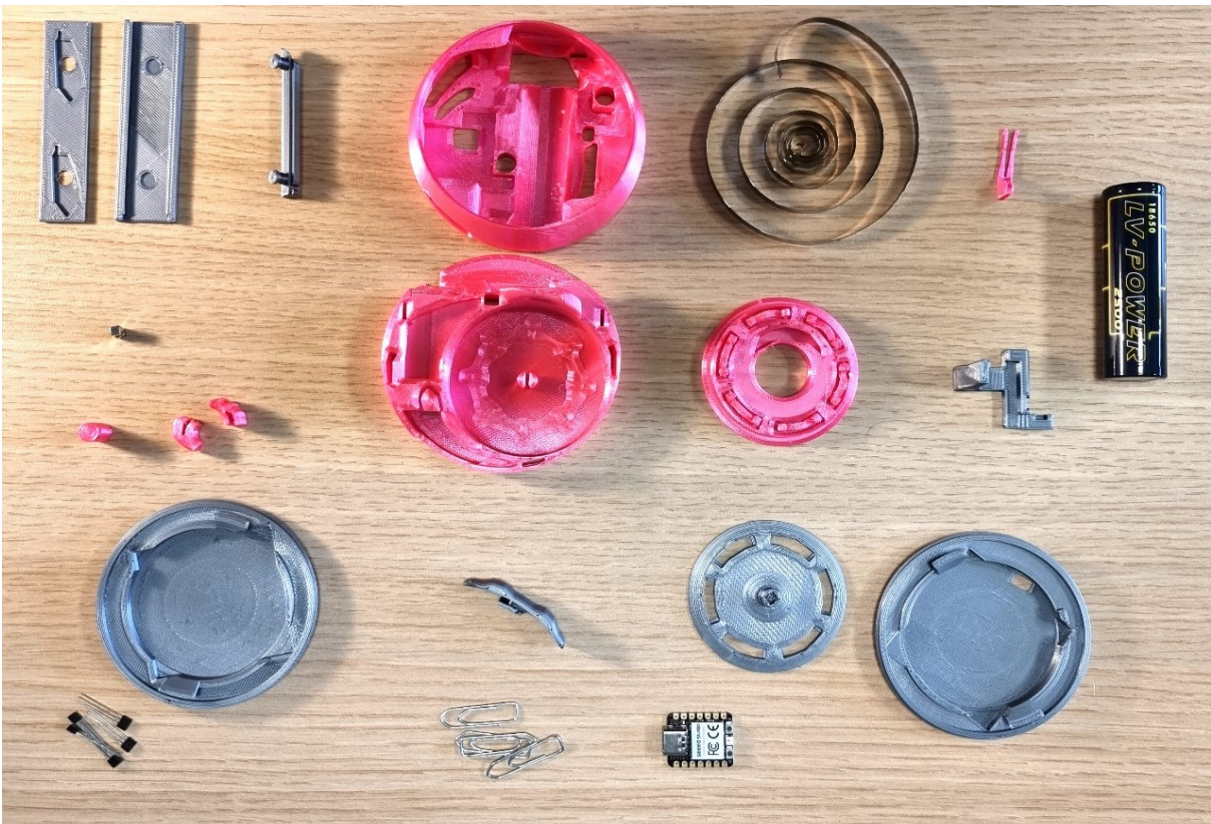


Figure B.8: Parts required for assembly of a SPART-ME M prototype

SPART-ME M SOFTWARE

The following code listing is version 2.0 of SPART-ME with an NFC shield.

```

1 #include <ArduinoBLE.h>
2 #include <Adafruit_PN532.h>
3
4 #define MINDISTANCEFORCHANGE 240
5 #define CIRCUMFERENCE 140
6 #define CORRECTOR_LENGTH -13
7 #define EPSILON 2.0
8
9 #define NFC_CYCLES 200
10 #define POSITION_SMOOTH 1
11
12 //reel sensor pins
13 #define PIN1 0
14 #define PIN2 1
15 //arm sensor pins
16 #define PIN3 2
17 #define PIN4 3
18
19 //data structures
20
21 struct Tuple {
22     float val1;
23     float val2;
24 };
25
26 struct NFCresponse {
27     boolean isNew;
28     String val;
29 };
30 //bluetooth setup
31 BLEService positionService("19B10010-E8F2-537E-4F6C-D104768A1214"); //
    create service
32 BLEStringCharacteristic getPos("19B10011-E8F2-537E-4F6C-D104768A1214",
    BLERead | BLENotify,20);

```

```

33 BLEService nfcService("19B10010-E8F2-537E-4F6C-D104768A1215"); // create
    service
34 BLEStringCharacteristic getNFC("19B10011-E8F2-537E-4F6C-D104768A1215",
    BLERead | BLENotify, 13);
35
36 struct Tuple amplitudesArm, amplitudesReel;
37 //Moving average in array
38 Tuple queue[30];
39 uint8_t queue_length = 20;
40
41 //SHIELD DEPENDENT
42 //NFC shield
43 #define PN532_IRQ    (9)
44 #define PN532_RESET (10) // Not connected by default on the NFC Shield
45 Adafruit_PN532 nfc(PN532_IRQ, PN532_RESET);
46 String nfc_status = "None";
47
48 //configured max values (device dependent)
49 float max1 = 2902;
50 float max2 = 2844;
51 float min1 = 1322;
52 float min2 = 1410;
53
54 float max3 = 2477;
55 float max4 = 2355;
56 float min3 = 1779;
57 float min4 = 1703;
58
59 float previousAngle;
60 struct Tuple previousCoordinates;
61 int rotationcounter = 0;
62 uint16_t cycle;
63
64 //FUNCTIONS
65 void initNFC(){
66     //NFC initialization
67     nfc.begin();
68     uint32_t versiondata = nfc.getFirmwareVersion();
69     if (! versiondata) {
70         sprintf("Didn't find NFC shield");
71         while (1);    }

```

```

72 }
73 //DEBUG
74 void sprint(String message){
75     // Serial.println(message);
76 }
77 void sprintInit(){
78     // Serial.begin(115200);
79     // while (!Serial){}
80     // Serial.println("serial online.");
81 }
82
83 uint32_t writeRegister(uint16_t address, uint8_t value) {
84     uint8_t pn532_packetbuffer[4];
85     pn532_packetbuffer[0] = PN532_COMMAND_WRITEREGISTER;
86     pn532_packetbuffer[1] = address >> 8;
87     pn532_packetbuffer[2] = address & 0xff;
88     pn532_packetbuffer[3] = value;
89
90     if (!nfc.sendCommandCheckAck(pn532_packetbuffer, 4))
91         nfc.sendAck();
92     return 1;
93 }
94
95 //takes a tuple queue and calculates averages for both values based on
96 //length argument
97 Tuple queue2average(uint8_t length, Tuple queue[]){
98     struct Tuple sum;
99     sum.val1 = 0.0;
100    sum.val2 = 0.0;
101    uint8_t counter;
102    for(counter = 0; counter<length;counter++){
103        sum.val1 += queue[counter].val1;
104        sum.val2 += queue[counter].val2;
105    }
106    sum.val1 /= length;
107    sum.val2 /= length;
108    return sum;
109 }
110 //function to account for unperfect magnetic fields
111 float correctorFunction(float angle){

```

```

112     return -4.31591e-07*pow(angle, 4)+0.000152772*pow(angle, 3)-0.016604*pow
        (angle, 2)+0.553877*angle;
113 }
114
115 //function to calculate position from length and angle
116 Tuple radial2Cartesian(float length, float angle){
117     struct Tuple coordinates;
118     coordinates.val1 = length * cos(angle*PI/180);
119     coordinates.val2 = length * sin(angle*PI/180);
120     return coordinates;
121 }
122
123 //function to calculate angles from values: First value - reel, second
        value - arm
124 Tuple values2Angles(Tuple valuesArm, Tuple valuesReel, Tuple amplitudesArm,
        Tuple amplitudesReel){
125     struct Tuple angles;
126
127     //norm and calculate angle
128     //reel
129     float norm1 = (valuesReel.val1 - min1 - amplitudesReel.val1) /
        amplitudesReel.val1;
130     float norm2 = (valuesReel.val2 - min2 - amplitudesReel.val2) /
        amplitudesReel.val2;
131     angles.val1 = -atan2(norm1, norm2) * 180 / PI;
132
133     //arm
134     float norm3 = (valuesArm.val1 - min3 - amplitudesArm.val1) /
        amplitudesArm.val1;
135     float norm4 = (valuesArm.val2 - min4 - amplitudesArm.val2) /
        amplitudesArm.val2;
136     angles.val2 = abs(atan2(norm3, norm4) * 180 / PI);
137     return angles;
138 }
139
140 //function to transform coordinates to String in cm
141 String coordinates2String(Tuple coordinates){
142     String message = "";
143     message = message +String(coordinates.val1/10,1);
144     message = message +", ";
145     message = message +String(coordinates.val2/10,1);

```

```

146     //message = message + "x";
147     return message;
148 }
149
150 //reads page 7-9 of NFC tag and returns it as string
151 String readString(Adafruit_PN532 nfc){
152     uint8_t data[4];
153     uint8_t counter = 0;
154     uint32_t szPos;
155     String message = "";
156     for(counter = 7; counter < 10; counter++){
157         uint8_t success = nfc.ntag2xx_ReadPage(counter, data);
158         for (szPos = 0; szPos < 4; szPos++) {
159             message = message + String((char)data[szPos]);
160         }
161     }
162     return message;
163 }
164
165 //function to check whether NFC has changed and if so writes new value into
166     nfc_status
167 NFCresponse isNewValue(Adafruit_PN532 nfc, uint8_t timeout){
168     uint8_t success;
169     uint8_t uid[] = { 0, 0, 0, 0, 0, 0, 0, 0 }; // Buffer to store the
170         returned UID
171     uint8_t uidLength; // Length of the UID (4 or 7
172         bytes depending on ISO14443A card type)
173     struct NFCresponse response;
174     success = nfc.readPassiveTargetID(PN532_MIFARE_ISO14443A, uid, &
175         uidLength, timeout);
176     //sprintf (String(success));
177     if(success){
178         String msg = readString(nfc);
179         if(nfc_status!=msg){
180             response.val = msg;
181             response.isNew = true;
182         } else
183             response.isNew = false;
184     } else {
185         String msg = "None";
186         if(nfc_status!=msg){

```

```

183         response.val = msg;
184         response.isNew = true;
185     } else
186         response.isNew = false;
187     }
188     return response;
189 }
190
191 void setup() {
192     //DEBUG-START
193     sprintInit();
194     initNFC();
195     //DEBUG-END
196     //make use of high resolution 12 Bit analog inputs :)
197     analogReadResolution(12);
198     //rotary element 1
199     pinMode(PIN1, INPUT);
200     pinMode(PIN2, INPUT);
201     //rotary element 2
202     pinMode(PIN3, INPUT);
203     pinMode(PIN4, INPUT);
204
205     //calc amplitudes of sensor ranges
206     amplitudesReel.val1 = (max1 - min1) / 2;
207     amplitudesReel.val2 = (max2 - min2) / 2;
208     amplitudesArm.val1 = (max3 - min3) / 2;
209     amplitudesArm.val2 = (max4 - min4) / 2;
210
211     //flush readings
212     analogRead(PIN1);
213     analogRead(PIN2);
214     analogRead(PIN3);
215     analogRead(PIN4);
216
217     //Bluetooth initialization
218     if (!BLE.begin()) {
219         sprint("starting Bluetooth Low Energy module failed!");
220         while (1);
221     }
222     BLE.setLocalName("SPART_NFC_prototype");
223     BLE.setAdvertisedService(positionService);

```

```

224     BLE.setAdvertisedService(nfcService);
225     positionService.addCharacteristic(getPos);
226     nfcService.addCharacteristic(getNFC);
227     // add the service
228     BLE.addService(positionService);
229     BLE.addService(nfcService);
230
231     getPos.writeValue("x0,0x");
232     getNFC.writeValue("None");
233     // start advertising
234     sprintf("starting advertising");
235     BLE.advertise();
236 }
237
238 void loop() {
239     BLE.poll();
240     struct Tuple voltagesArm, voltagesReel, angles, coordinates;
241     //get values from sensors
242     //reel
243     voltagesReel.val1 = analogRead(PIN1);
244     voltagesReel.val2 = analogRead(PIN2);
245     //arm
246     voltagesArm.val1 = analogRead(PIN3);
247     voltagesArm.val2 = analogRead(PIN4);
248
249     angles = values2Angles(voltagesArm, voltagesReel, amplitudesArm,
250                           amplitudesReel);
251     //compare to previous value: if change from -180 to 180 or vice versa,
252     //then count a new rotation from reference point and overwrite
253     //buffervalues
254     if(abs(angles.val1-previousAngle)>MINDISTANCEFORCHANGE) {
255         uint8_t buffer_counter;
256         if(angles.val1 > 0){
257             rotationcounter--;
258             for(buffer_counter = 0; buffer_counter<queue_length;
259                buffer_counter++)
260                 queue[buffer_counter].val1 += 360;
261         } else {
262             rotationcounter++;
263             for(buffer_counter = 0; buffer_counter<queue_length;
264                buffer_counter++)

```

```

260         queue[buffer_counter].val1 -= 360;
261     }
262 }
263 //keep track of reel angle
264 previousAngle = angles.val1;
265
266 //add to queue, then calc average
267 queue[cycle%queue_length].val1 = angles.val1;
268 queue[cycle%queue_length].val2 = angles.val2;
269
270 //ONLY EVERY X CYCLES:
271 if(cycle%POSITION_SMOOTH==0){
272     //calculate average angle
273     struct Tuple smoothedAngles = queue2average(queue_length, queue);
274     //sprintf(String(angles.val1,1)+" "+String(angles.val2,1)+" "+String
275         (smoothedAngles.val1,1)+" "+String(smoothedAngles.val2,1));
276     //correct angle with corrector function (no round magnet -> field
277         not homogenous)
278     float correctedAngle = smoothedAngles.val2 + correctorFunction(
279         smoothedAngles.val2);
280     //sprintf(String(correctedAngle));
281     float length = CORRECTOR_LENGTH + rotationcounter * CIRCUMFERENCE +
282         CIRCUMFERENCE * (smoothedAngles.val1+180) / 360;
283     //sprintf(String(length,2));
284     coordinates = radial2Cartesian(length, correctedAngle);
285     //update bluetooth position characteristic only if position changed
286     //sprintf(String(coordinates.val1,1)+" "+String(coordinates.val2,1))
287     ;
288     if(abs(previousCoordinates.val1 - coordinates.val1)>EPSILON || abs(
289         previousCoordinates.val2 -coordinates.val2)>EPSILON ){
290         //Serial.println("New position");
291         getPos.writeValue(coordinates2String(coordinates));
292         previousCoordinates = coordinates;
293         sprintf(String(coordinates.val1,1)+" "+String(coordinates.val2
294             ,1));
295     }
296 }
297
298 //try starting NFC later after 10000 cycles
299 //ONLY EVERY X CYCLES
300 if(cycle%NFC_CYCLES==0){

```

```
294     //check NFC status
295     struct NFCresponse nfc_change = isNFCnewValue(nfc, 50);
296     sprint(nfc_change.val);
297     if(nfc_change.isNew){
298         nfc_status = nfc_change.val;
299         sprint("state change: "+nfc_status);
300         getNFC.writeValue(nfc_change.val);
301     }
302     nfc.SAMConfig();
303 }
304 cycle++;
305 delay(2);
306 }
```

STUDY 1 - ACTIVITY ASSIGNMENT

Mission Géologie

C'est l'année 1967, votre collègue, Jason Morgan, veut convaincre le congrès de l'union américaine géophysique, une fois pour toutes, qu'il y a plusieurs plaques terrestres qui flottent, comme le fromage gratiné, sur le cœur liquide de la terre. Il y a toujours de nombreux chercheurs connus, comme Harold Jeffreys, qui s'y opposent fermement. C'est une discussion qui fait débat depuis plus de 50 ans !

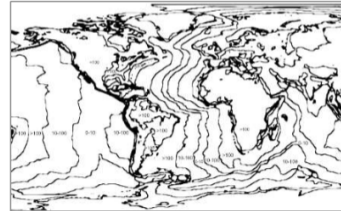
Votre collègue compte sur vous pour identifier ces plaques, comment elles bougent et expliquer leurs mouvements. Des chercheurs du monde entier travaillent pour dater l'âge des sols et recenser la position et la profondeur des séismes. Récemment, ils ont réussi à dater l'âge des fonds océaniques. Les données vous sont disponibles en exclusivité. Le congrès est dans une semaine, Jason devra préparer son discours ce soir. Serez-vous à la hauteur ?

1. D'abord vous voulez visualiser, sur une carte, l'âge des roches basaltiques qui constituent le plancher océanique (*annexe 2*). Pour cela, **colorez le plancher océanique** de la carte imprimée en A3 avec des crayons de couleur en respectant la légende suivante :

Rouge = zone entre 0 et 10 millions d'années

Jaune = zone entre 10 et 100 millions d'années

Vert = zone plus âgée que 100 millions d'années



Super ! Vous avez devant vous une « photo » du passé : Si la croûte de la terre se renouvelle constamment, on devrait voir son mouvement grâce à l'âge différent du sol. Quelles sont vos hypothèses sur la direction (et la vitesse) des mouvements du sol ? (En cas de difficulté, vous pouvez consulter les *indices 1 et 2* en annexe)

2. Jason vient de vous envoyer les données sismiques mondiales (ci-dessous) ! Tous les tremblements de terre y sont (points bleu clair), ainsi que les activités volcaniques (triangles rouges) dont on a connaissance aujourd'hui (indice 2).

Tracer au feutre noir, les contours des plaques tectoniques en vous servant des informations sur l'âge du plancher océanique (la carte que vous venez de colorier) et les informations sur l'activité sismique et volcanique (ignorer les numéros sur la carte pour le moment).

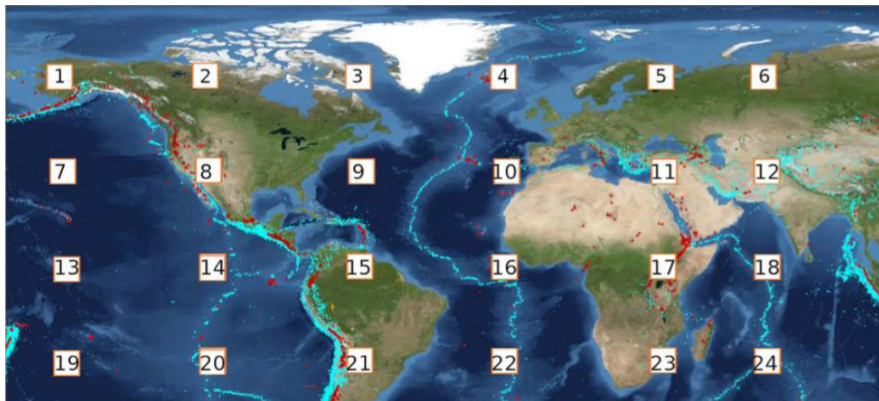
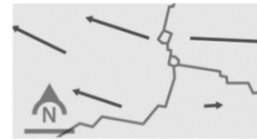


Figure D.1: Page 1 of the activity assignment (french)

3. Réfléchissez dans quel sens les plaques bougent : **Ajouter des flèches au feutre noir**, sur la carte, pour montrer le sens de déplacement des plaques terrestres. Le plus de détails Jason peut donner lors de son discours, le plus il a des chances pour convaincre ses collègues !



4. Un livreur sonne à la porte. Le colis des Etats-Unis contient 24 schémas (*annexe*). Jason vous a préparé des schémas qui contiennent les informations sur la profondeur des foyers sismiques (et volcaniques) pour chacun des endroits numérotés sur la carte *activité sismique et volcanique*. Cette fois-ci, vous avez les informations sur la profondeur de l'activité sismique et sa position au long d'une droite dans la direction de la flèche (par exemple coupe n° 14 montre des tremblements dans une profondeur de 10km sur 1000km de l'ouest à l'est).

Motivés, vous analysez les coupes afin de déterminer la position et le type de zones dans laquelle les relevés sismiques et volcaniques ont été réalisés. Complétez le **tableau suivant sur une feuille à part** en notant les numéros des coupes ou des relevés qui correspondent aux zones identifiées :

Type de zone		Numéros des relevés							
Zone stable (pas d'activité sismique et volcanique)		2							
Zone active (activité sismique avec des foyers majoritairement entre 0 et 100km de profondeur)	Au niveau d'un océan								
	Au niveau d'un continent								
Zone active (activité sismique avec des foyers sismiques supérieurs à 100km de profondeur)									

Tableau à remplir sur une feuille à part

Le téléphone sonne. Jason vous explique qu'il espère que les coupes vous permettront de lui dire plus sur le comportement des plaques là où elles rentrent en collision. Quelles sont vos conclusions ? (*Indice 3*)

5. Aider des scientifiques en répondant à leurs questions (à écrire sur une feuille séparée) :

- **Question 1 :** On observe des zones de coloriage symétrique autour de certaines zones actives. Pourquoi ?
- **Question 2 :** Autour de la zone active du Pacifique, on observe bien cette symétrie, mais il manque la zone la plus ancienne (verte) vers l'Amérique du Sud. Où est-elle passée ?
- **Question 3 :** Comment l'observation de la répartition des foyers sismiques au niveau de la zone active vers l'Amérique du Sud (coupe n° 21) pourrait-elle expliquer où a disparu ce plancher océanique ancien ?
- **Question 4 :** Rédigez un petit discours montrant votre découverte au niveau de la fosse bordant l'Amérique du sud permettant ainsi de mieux comprendre le mouvement des plaques et confirmant ainsi la théorie de la tectonique des plaques.

Figure D.2: Page 2 of the activity assignment (french)

Indices :

Vous vous rappelez d'une conversation avec Jason lors de votre dernier voyage aux Etats-Unis :

- Jason : « You know dear, les zones d'accrétions entre plaques tectoniques sont faciles à identifier. Elles se trouvent au milieu des zones de planché océanique les plus jeunes. Amazing, isn't it! (Indice 1)

- Vous : « Ah oui ! Donc, plus la zone jeune est large, plus les plaques s'écartent vite ? » (Indice 2)

- Jason : « Wow, right ! Mais vous savez...il y a quelque chose qui m'inquiète. Devant le Chili le plancher est jeune, mais la plaque sur lequel repose le Chili est super ancien ! Il n'y a pas de transition ! Comme si le plancher...disparaissait d'un coup ?! Mysterious... Peut-être des coupes de profondeur pourraient nous aider ? Vu que les tremblements nous montrent où les plaques se frottent ?! (Indice 3)

Annexe 1 : Coupes en profondeur de la carte sismique et volcanique

➡ Sens de la coupe sur la carte orientée Nord

Chaque point rouge correspond à un tremblement de terre. Chaque triangle correspond à une activité volcanique.

La couleur bleue correspond à un volume d'eau, la couleur grise correspond à la roche.

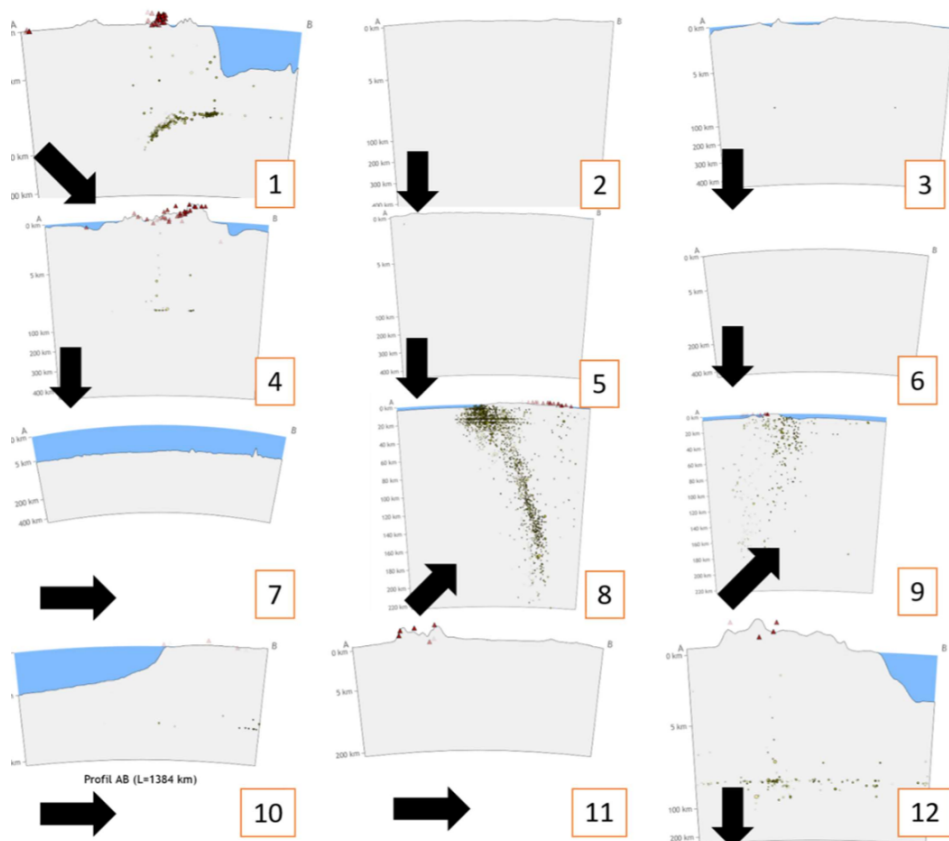


Figure D.3: Page 3 of the activity assignment (french)

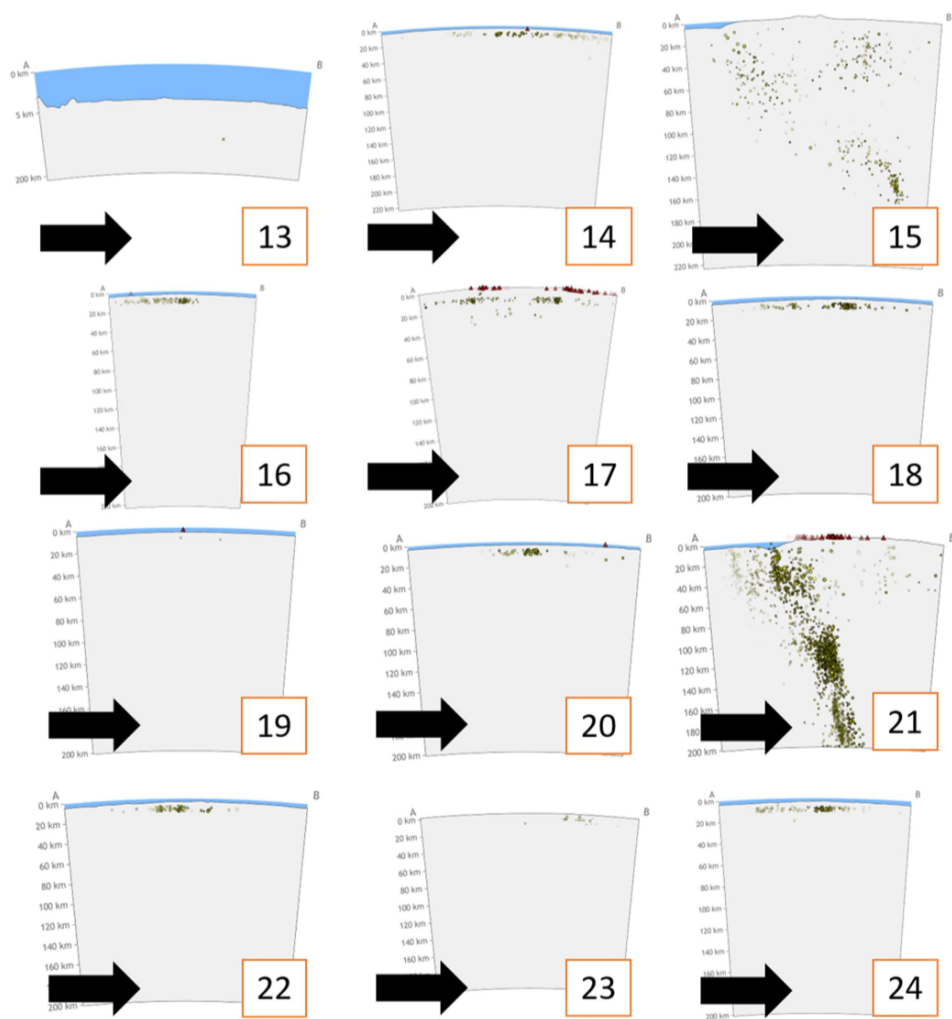


Figure D.4: Page 4 of the activity assignment (french)

STUDY 2 - ACTIVITY ASSIGNMENT

Sujet Groupes SPART

Titre : Comment se loger ? Se repérer dans l'espace et savoir utiliser une clé de détermination

Description : Même s'ils paraissent immobiles et non-vivant, les plantes sont des êtres vivants complexes. Allez faire leur connaissance ! Savez-vous comment ils s'appellent ? Ça serait dommage de ne pas pouvoir s'adresser correctement à eux.

Heureusement qu'il y a la clé de détermination ! Vous avez donc deux tâches :

1. Trouver leur milieu de vie dans la cour
2. Placer le symbole des bons arbres au bon endroit sur la carte de la cours (annoter la carte avec les symboles de la clé)

Vous pouvez vous servir de l'application pour vérifier vos réponses ou avoir des astuces. Vous devez vous mettre d'accord sur le **type** et la **position** de chacun des **10 arbres** dans la cour de votre collège. Pour chaque bonne réponse vous gagnez des points et on vous dira quel groupe aura gagné à la fin !

Jetons : vous avez chacun dans votre groupe un jeton que vous pouvez poser sur le petit boîtier pour vous aider.

Jeton Oiseau : image de satellite pour mieux se repérer/Accès à vérification immédiate

Jeton Loupe : donne accès aux feuilles et aux épines de l'arbre là où vous appuyez sur l'écran. Si c'est le mauvais endroit, il se peut qu'il y ait des feuilles d'autres arbres...

Jeton Arbre : permet de voir la zone (le milieu de vie) où se trouvent les arbres

Points : vous gagnez des points pour chaque arbre correctement positionné (+3) et pour chaque type d'arbre correctement identifié (+5). Vous pouvez immédiatement vérifier si un arbre est bien placé et typé. Chaque vérification vous coûte un point.

***Symboles à placer sur la carte :**



Clé de détermination

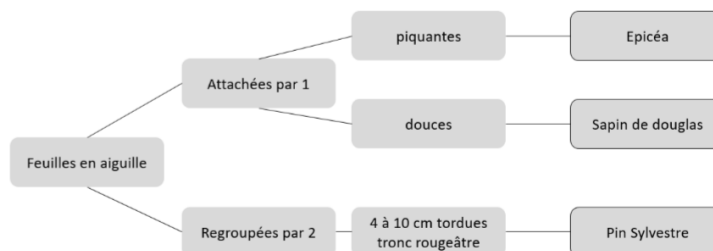


Figure E.1: Activity assignment handed out to students in SPART groups (french)

Sujet Groupes Sans Prototype

Titre : Comment se loger ? Se repérer dans l'espace et savoir utiliser une clé de détermination

Description : Même s'ils paraissent immobiles et non-vivant, les plantes sont des êtres vivants complexes. Allez faire leur connaissance ! Savez-vous comment ils s'appellent ? Ça serait dommage de ne pas pouvoir s'adresser correctement à eux.

Heureusement qu'il y a la clé de détermination ! Vous avez donc deux tâches :

1. Trouver leur milieu de vie dans la cour
2. Placer le symbole des bons arbres au bon endroit sur la carte de la cours (annoter la carte avec les symboles de la clé)

Pour chaque bonne réponse vous gagnez des points et on vous dira quel groupe aura gagné à la fin !

Matériel : Vous avez à votre disposition plusieurs vues de la même carte :

- *Couche Satellite* pour mieux se repérer/accès à vérification immédiate
- *Couche milieu* : Permet de voir la zone (le milieu de vie) où se trouvent les arbres
- *Monsieur Théard* : Il se peut que vous n'avez pas accès aux feuilles des arbres. Vous pouvez aller voir Monsieur Théard pour lui demander des « feuilles » en lui montrant l'endroit sur la carte qui vous intéresse.

Points : Vous gagnez des points pour chaque arbre correctement positionné (+3) et pour chaque type d'arbre correctement identifié (+5). Vous pouvez immédiatement vérifier si un arbre est bien placé et typé en demandant à Monsieur Théard. Chaque vérification vous coûte un point.

***Symboles à placer sur la carte :**

Epicéa



Sapin de douglas



Pin Sylvestre



Clé de détermination

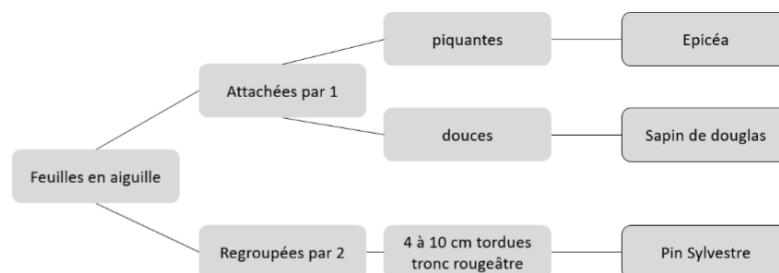


Figure E.2: Activity assignment handed out to students in control groups (french)

Questionnaire

1. L'outil m'a aidé pour atteindre l'objectif de cette séance : 1 Pas du tout – 5 Tout à fait
2. J'ai rapidement compris comment l'outil peut m'aider : 1 Pas du tout – 5 Tout à fait
3. J'ai déjà travaillé avec les autres membres du groupe en groupe : Oui – Non
4. Je pense que tous les membres du groupe ont pu utiliser l'outil : 1 Pas du tout – 5 Tout à fait
5. J'ai été frustré par l'expérimentation : Oui – Non, Parce que _____
6. L'objectif de la séance était de _____
7. L'utilisation de l'outil a rendu plus dur la séance : 1 Pas du tout – 5 Tout à fait
8. La collaboration pour moi est : _____
9. J'aurais bien aimé avoir une fonctionnalité de plus : Oui, celle-ci : _____-Non
10. Je trouve que l'outil aide à mieux _____

Items du F-SUS	1. Pas du tout d'accord	2	3	4	5. Tout à fait d'accord
1. Je voudrais utiliser ce système fréquemment	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. Ce système est inutilement complexe	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. Ce système est facile à utiliser	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. J'aurais besoin du soutien d'un technicien pour être capable d'utiliser ce système	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5. Les différentes fonctionnalités de ce système sont bien intégrées	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6. Il y a trop d'incohérences dans ce système	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7. La plupart des gens apprendront à utiliser ce système très rapidement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8. Ce système est très lourd à utiliser	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9. Je me suis senti·e très en confiance en utilisant ce système	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
10. J'ai eu besoin d'apprendre beaucoup de choses avant de pouvoir utiliser ce système	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure E.3: Questionnaire handed out to students after the activity (french)

RÉSUMÉ LONG EN FRANÇAIS

Cette thèse de doctorat a été menée au sein de l'équipe IEIAH (Ingénierie des Environnements Informatiques pour l'Apprentissage Humain) du Laboratoire d'Informatique de l'Université du Mans (LIUM). Elle fait partie du projet ANR SituLearn, qui fournit aux enseignants un outil auteur leur permettant de créer des applications mobiles pour des sorties pédagogiques ludiques. Dans ce contexte, l'objectif principal de la thèse est de concevoir un dispositif mobile, matériel et logiciel, pour soutenir la collaboration entre groupes d'apprenants autonomes. La première question de recherche porte sur la conception d'un dispositif capable de soutenir l'apprentissage collaboratif et situé. Après avoir recensé les outils collaboratifs existants dans la littérature, nous avons émis l'hypothèse qu'une interaction de type « peephole dynamique » horizontale, permettant d'augmenter un support statique via un appareil mobile (comme un smartphone ou une tablette), était adaptée pour cet usage. Concrètement, il s'agit de faire glisser un ou plusieurs smartphones sur une surface plane (telle qu'une carte du lieu de la sortie pédagogique) pour afficher des éléments numériques (par exemple des informations sur des arbres, l'emplacement d'anciens remparts ou la localisation d'autres apprenants). Ce type d'interaction a pour objectif d'offrir les mêmes atouts que les tables interactives, un des dispositifs les plus étudiés pour faciliter la collaboration dans la littérature. Cette réflexion a conduit à la question suivante :

Q1 : L'interaction avec un appareil mobile, capable d'augmenter un support statique (tel qu'une carte), constitue-t-elle un support pertinent pour l'apprentissage collaboratif et situé ? Et, si oui, sur quels aspects de la collaboration agit-elle spécifiquement ?

Afin de répondre à cette question, nous avons conçu et développé le dispositif SPART (on-Surface Positioning Augmented Reality). Le développement matériel de SPART a représenté un défi majeur, car aucun autre outil sur le marché, ni prototype de recherche, ne propose ce type d'interaction. Une fois la partie matérielle développée, la conception de la partie logicielle a soulevé des enjeux tout aussi importants. Plus précisément, la question de savoir quelles fonctionnalités seraient pertinentes pour un logiciel collaboratif s'est révélée centrale. Ceci nous a amenés à poser la question suivante :

Q2 : Existe-t-il une liste exhaustive de fonctionnalités pour les outils collaboratifs ? Quels sont leurs impacts sur la collaboration ? Et comment différentes combinaisons de ces fonctionnalités influencent-elles les processus collaboratifs ?

Après avoir mené un état de l'art sur la littérature à ce sujet, nous avons constaté l'absence d'une liste ou analyse exhaustive de fonctionnalités pour la collaboration. Nous avons donc mené une méta-analyse des travaux existants pour identifier ces fonctionnalités, mais aussi leurs impacts sur la collaboration. Cependant, ce travail nous a amenés à nous interroger sur l'existence d'une définition précise de la collaboration ou d'un cadre conceptuel qui identifie clairement les éléments et mécanismes en jeu. D'où la question suivante :

Q3 : Dans le domaine du CSCL (Computer-Supported Collaborative Learning), qui réunit des chercheurs de disciplines variées (psychologie, informatique, sociologie, etc.), existe-t-il une vision conceptuelle commune de la collaboration ? Si ce n'est pas le cas, est-il possible de combiner les visions existantes ?

Ces trois questions de recherche ont guidé nos travaux au cours de cette thèse et ont abouti à plusieurs contributions. Dans un premier temps, nous avons réalisé **un état de l'art systématique** sur les technologies susceptibles de répondre aux besoins du dispositif SPART, c'est-à-dire une interaction de type "peephole dynamique" horizontale (Q1). La difficulté est de trouver une technologie mobile et abordable capable de localiser un smartphone de façon très précise sur une surface plane. Afin d'explorer l'ensemble des solutions possibles de façon systématique, nous avons cherché toutes les technologies possibles en combinant les phénomènes physiques et les techniques de localisation. À la suite de cet état de l'art, nous avons développé et testé **7 prototypes de SPART** (magnétiques, mécaniques et acoustiques). Deux d'entre eux, en particulier, ont abouti à des versions conformes aux critères établis dans l'analyse précédente. En parallèle, pour tenter de comprendre les éléments et mécanismes inhérents à la collaboration (Q3), nous avons établi **des définitions** des concepts de **collaboration, d'apprentissage collaboratif et le domaine du CSCL** (Computer Supported Collaborative Learning), fondées sur un état de l'art. Les résultats révèlent à la fois la diversité des définitions existantes, mais aussi un tronc commun de concepts mobilisés et partagés entre les domaines. Nous avons

donc repris ces concepts communs pour établir une vision détaillée de la collaboration à travers un **cadre conceptuel**. Ce cadre se nomme **PAC framework** pour reprendre les trois aspects fondamentaux que nous avons identifié pour la collaboration : Participation (le fait que chaque apprenant participe à l'activité), Awareness (le fait d'être conscient des actions, mais aussi des compétences des autres) et Coordination (le fait de s'organiser en groupe). Ce cadre est basé sur un état de l'art des cadres conceptuels de collaboration et combine également des cadres proposés pour la conception et l'analyse d'outils numériques collaboratifs. Le PAC framework offre ainsi une vue d'ensemble des travaux dans le domaine et met en lumière les liens entre les différents processus collaboratifs, les conditions d'interaction et les détails des activités. Il a été construit dans le but de devenir un artefact collaboratif pour la communauté CSCL.

En outre, nous avons mené une **méta-analyse sur les fonctionnalités collaboratives existantes** (Q2). Celle-ci nous a permis d'identifier **une liste de 20 fonctionnalités** collaboratives classées en six catégories, mais aussi de mesurer **leurs impacts potentiels** sur les trois aspects de la collaboration (Participation, Awareness et Coordination). Nous avons également mené des analyses sur des combinaisons de fonctionnalités qui suggèrent que combiner plusieurs fonctionnalités transforme l'impact sur la collaboration du logiciel.

Cette méta-analyse nous a permis de faire un choix informé concernant les fonctionnalités à développer dans SPART afin de mener **deux études sur le terrain**. **La première étude** a été réalisée avec une classe de 32 collégiens, dans le cadre d'un cours sur la tectonique des plaques en SVT. En groupe de quatre, les élèves étaient amenés à émettre et tester des hypothèses sur le mouvement relatif des plaques tectoniques. Une carte mondiale a été fournie comme support statique sur laquelle la tablette permettait de visualiser différentes données (ex. âge du plancher océanique, coupes verticales des séismes). Grâce à l'analyse détaillée des vidéos et la mise en relation des observations avec le PAC framework, nous avons pu montrer que SPART servait de support visuel pour faciliter les échanges oraux et aider également les apprenants à savoir où en étaient leurs camarades dans leurs raisonnements. **La deuxième étude** s'est déroulée dans la cour d'un collège avec 24 élèves. En petits groupes, les élèves devaient annoter une carte de la cour en y indiquant la position et le type des arbres présents, à l'aide d'une clé de détermination simplifiée. Cette sortie s'est fait une semaine après la sortie avec l'outil SituLearn, pendant laquelle les apprenants avaient déjà exploré les caractéristiques des arbres de la cour. Grâce à la conception modulaire de SPART, nous avons pu ajouter une fonctionnalité

supplémentaire d'interdépendance positive, à travers des jetons d'accès personnalisés. Les membres du groupe avaient ainsi accès à différentes informations numériques en utilisant leurs jetons (ex. la position des arbres, l'affichage des feuilles). Cette étude a permis de consolider les résultats précédents puisqu'elle montre une collaboration plus prononcée dans les groupes utilisant SPART.

Afin de tester la robustesse et l'ergonomie des prototypes SPART, nous avons également mené un **test d'utilisabilité** lors d'une exposition scientifique ouverte au grand public, par le biais d'un petit jeu augmenté, dont les résultats confirment le choix de l'interaction comme ergonomique et intuitif. Ces trois études ont souligné le rôle de SPART comme support adéquat pour lier l'abstrait au réel en fournissant des visualisations ou données sur un support plan telles qu'une carte. Les contributions de la thèse ont été publiées dans des conférences en informatique, IHM et CSCL. La première version du PAC framework a été présentée à la conférence EC-TEL en 2022, suivie de la méta-analyse sur l'impact des fonctionnalités collaboratives à ISLS/CSCL 2023. Le premier prototype fonctionnel de SPART a été dévoilé à Mobile Learning 2024 et nous a valu le prix de best paper. Les résultats de la première expérimentation ont été présentés à CSEDU 2024 et le second prototype de SPART, lors d'un atelier sur la collaboration à IHM 2024. Enfin, la version étendue du PAC framework a été exposée à ISLS/CSCL 2024. En conclusion, cette thèse apporte des contributions significatives à la fois sur le plan théorique, en proposant un cadre conceptuel pour l'analyse des processus collaboratifs, et sur le plan pratique, avec la conception d'un prototype d'interaction collaborative augmentée pour des environnements mobiles. Ces résultats sont également discutés dans le cadre du modèle SituLearn, afin de proposer des perspectives d'amélioration des outils et méthodes pour l'apprentissage collaboratif contextualisé.

Titre : Apprentissage collaboratif en situation de mobilité : cadre conceptuel et conception d'un dispositif pour augmenter des représentations visuelles planes

Mot clés : Apprentissage Situé, Apprentissage Collaboratif Assisté par Ordinateur, Interaction Peephole, mobilité

Résumé : Cette thèse de doctorat est centrée sur la conception et l'expérimentation d'un outil pour soutenir l'apprentissage collaboratif, en petits groupes autonomes, lors de sorties sur le terrain. À cette fin, nous avons développé SPART, un dispositif d'augmentation de surfaces planes, par exemple des cartes ou des images, qui peut être utilisé avec des smartphones ou des tablettes standards. Il offre un grand espace de travail et des interactions intuitives similaires aux tables interactives. Ce dispositif a été testé dans le cadre d'une activité en classe, d'une sortie pédagogique et d'une exposition scientifique. Cette thèse propose également des contri-

butions plus théoriques comme la définition d'un cadre conceptuel pour mieux comprendre les éléments et les mécanismes inhérents à l'apprentissage collaboratif instrumenté. Le cadre de conception, nommé PAC Framework, a été construit en considérant un grand nombre de travaux scientifiques, dans le but de devenir un artefact collaboratif pour la communauté CSCL (Computer Supported Collaborative Learning). Nous proposons également une méta-analyse des fonctionnalités collaboratives existantes et de leurs impacts sur les activités et les apprentissages pour guider la conception de logiciels CSCL.

Title: Collaborative Learning in Mobile Settings: Conceptual Framework and Design of an Innovative Device to Augment Flat Visual Representations

Keywords: Situated Learning, Collaborative Learning, Peephole Interaction, Computer Supported Collaborative Learning, mCSCL

Abstract: This PhD thesis focuses on the design and experimentation of a tool to support collaborative learning, in small autonomous groups, during field trips. To this end, we have developed SPART, a device for augmenting flat surfaces, such as maps or images, which can be used with standard smartphones or tablets. It provides a large workspace and intuitive interaction affordances similar to those offered by interactive tabletops. The device has been tested during a classroom activity, a field-trip and a science fair. This the-

sis also offers more theoretical contributions, such as a definition of a conceptual framework, to better understand the elements and mechanisms inherent to collaborative learning. The PAC conceptual framework was built with the aim of becoming a collaborative artifact for the CSCL (Computer Supported Collaborative Learning) community. We also propose a meta-analysis of existing collaborative functionalities and their impacts to facilitate the design of CSCL software.