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SOS: Orchestrating Collaborative Activities across Digital and Physical Spaces Using Wearable Signaling Devices

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Abstract: Carrying out collaborative learning activities (supported by technologies or not) typically involves the coordination of multiple participants, in their dynamic assignment to groups and roles and in the distribution of resources and tools to specific group or individuals. While the mechanisms required to address these coordination aspects in digital educational spaces have been largely studied, less research has been conducted on orchestration support for facilitating this coordination in (technology-enhanced) physical spaces, such as the classroom or the playground. This paper presents the Signal Orchestration System (SOS), a system that augments the physical environment with digital signals indicating orchestration aspects. The SOS facilitates its integration with digital educational spaces to allow transitioning activities from digital to physical spaces. The paper describes the SOS system and its underlying architecture through a functional prototype that has been developed to show its feasibility and to enable its evaluation in authentic situations. The main components of the prototype include a Manager, where orchestration visual and auditory signals are configured, changed on the fly and transmitted, and three different designs of Wearable Signaling Devices, which are carried by participants and render the orchestration signals. The prototype has been used in two different experiments in the context of a real course applying adaptations of the well-known Jigsaw collaborative learning flow pattern. The results show that the SOS enables a flexible dynamic orchestration of the collaborative activities.

Keywords: activities across spaces, CSCL, collaborative learning flows, classroom orchestration, augmented physical spaces, wearable devices
Categories: K.3, K.3.0, K.3.1, L.6.2, L.7.0

1 Introduction

Digital educational spaces in Computer-Supported Collaborative Learning (CSCL), such as learning management systems (LMS) or task-specific software tools, are expected to mediate social interactions as key activators of learning. However, a concern in CSCL is that free collaboration does not necessarily produce fruitful learning and, that in certain circumstances, coordination and structuring facilities should be provided to increase the probability of reaching successful outcomes [Dillenbourg, 09a]. The specification of collaborative learning flows that shape (or script) the collaboration processes supported by these spaces has been proposed as a solution to address this concern. The aim of these structured flows is to guide students in a process involving knowledge intensive social interactions (e.g., socio cognitive conflict, mutual explanation, positive interdependence, etc.). The flows typically

require a sophisticated coordination of a set of activities, involving a dynamic group formation, assignment of roles, distribution of resources and tools to specific groups or individuals, etc. [Hernandez-Leo, 07; Kobbe, 07; Harrer 08].

However, physical environments, such as the classroom, the playground, the countryside, the city or a museum are also used as learning spaces in which collaborative learning activities can be carried out [Oblinger, 05]. Implementing flows of collaborative learning activities in physical spaces is demanding for teachers, not only because it implies a dynamic managing of multiple learners and tools (technology-based or not), but also because it involves a coordination overhead. This overhead takes a time within the classroom session that needs to be minimized and represents an important teachers' workload that can divert their attention from the actual learning task [Suthers, 07].

Technologies are also applied to augment educational physical spaces. Artifacts such as tabletops, smartboards, netbooks, multitouch screens, PDAs, lanterns and tangible building blocks have been proposed to support enhanced learning activities in the physical space. These devices are augmenting the reality, across physical and digital spaces, in the sense that they overlay and add digital information to real objects or integrate computer power into them [Alavi, in press; Dillenbourg, 09b; Mäkitalo-Siegl, 10]. Existing contributions are very valuable solutions to support specific activities and transversal aspects of collaboration processes, such as personal response systems for facilitating participation in collective activities [Moss, 11], single display connected to multiple mice to support large group collaboration [Szewkis, 11], using netbook or tablet computers to aid discussion by swap-ing students' thoughts [Dickey-Kurdziolek, 10] or to share scribbles in visual spaces [Dimitriadis, 07], ambient awareness for supervising collaboration [Alavi, in press], etc. However, these approaches do not offer orchestration mechanisms integrated in physical spaces for seamlessly coordinating collaborative learning flows.

In addition, activities in physical spaces are many times designed by teachers in a way that are integrated in larger learning processes where there are follow-up (or/and previous) activities in the classroom or at home, and in which students may be asked to keep collaborating using a software environment in the digital space. Mobile technologies are being particularly used for supporting the data flow required by these activities across the spaces [Mullholland, 12; Pérez-Sangustín, 12]. However, the existing proposals do not solve the coordination aspects that appear in a collaborative classroom.

This paper emphasizes the need for a technology-supported layer to address the identified problems: facilitate the coordination of collaborative learning flows in the classroom and its possible continuation in activities beyond the classroom. The paper conceptualizes and proposes the architecture and an implementation of the Signal Orchestration System (SOS), a system that augments the physical environment with digital signals indicating collaborative learning flow orchestration aspects. The SOS consists of a manager and a set of signaling devices that can be worn by participants or attached to resources of specific areas in the physical space. The orchestration signals are configured in the manager (e.g., light colors indicating group formation, blinking lights signifying role distribution, sounds announcing change of activity) and transmitted to the wearable devices, which render the signals. It is designed for face-to-face scenarios. Depending on the educational situation, teachers or facilitators (or a

similar actor, henceforth referred to as "teacher") will typically control the manager on-the-fly in combination with less structured processes also present in collaborative scenarios (e.g., negotiation, brain storming…) and with social / verbal indications to explain the rationale of the learning flow signaled by the system. The architecture of the SOS is extensible and includes an interoperability module that, if integrated with LMSs or task-specific software tools, enables the transition of activities from digital to physical educational spaces, and the other way around. The current implementation of the SOS is a proof-of-concept that allows evaluating the approach in practice as part of a design-based research methodology [Amiel, 08]. The system has been designed to serve any institutional context applying collaborative practices, though the conducted experiments have been framed in higher education contexts.

It worth mentioning that while signaling could be done using mobile phones, the SOS devices are designed so that both the individual and the group perceive the signals, facilitating group awareness. The information through phones could be more detailed, but less visible and unshared. In this sense, both approaches can be used to support activities complementary. Nevertheless, if additional information is not required as part of a learning activity, the SOS devices provide a minimalist and lower-cost solution. Phones tend to be more expensive and sometimes it is difficult for teachers to ensure that every student will own one that is compliant with the system requirements. Moreover, students' attention to the activity can be affected if they play with other mobile applications. In some countries teachers of schoolchildren are reluctant to allow learners to make use of mobile phones in school time, or are prohibited from doing so. Wearable devices can be designed to be more generic and usable by students at all educational levels; the classroom, the playground, etc.

The paper describes the logic and physical layers of the SOS architecture and the implemented system prototype in Section 2. The prototype shows the feasibility of the proposed system as it enabled its evaluation with users in real settings. In particular, the SOS has been used in two experiments in the same educational setting, applying two adaptations of a Jigsaw-based educational design requiring diverse orchestration mechanisms. The first experiment only used one type of wearable device and color signals [Hernández-Leo, 10], while the second experiment uses more types of signals (sounds, blinking lights) and three different physical designs of the wearable devices (Necklace, Belt, Textile). Section 3 explains the two educational designs and offers the aggregated evaluation of the two experiments. Finally, conclusions and future work are given in Section 4.

2 Signal Orchestration System

The Signal Orchestration System (SOS) is composed out of a software platform and hardware devices with signaling capabilities of different nature (e.g., visual, auditory, haptic) that can be customized to run orchestrated collaborative activities in constrained physical spaces, such as the classroom or the playground. The SOS can be broken down into a Signal Orchestration Manager and Wearable and Fixed Signaling Devices as the main components of the SOS system architecture.

In a typical configuration each student has a device that can be set to signal collaborative learning flow coordination aspects. Other resources or furniture in the physical space can also be associated to a fixed device. A teacher determines the

signals in the manager and distributes them to all of the devices or a selection of them. Configuration of the orchestration signals depends on the characteristics of the desired collaborative learning flow, the number of participants and the availability of required resources and work areas, and the creativity of the teacher. These orchestration signals include, but are not limited to, group formation (membership identification), role assignment and rotation (e.g., speakers / listeners within the group), distribution of resources (e.g., shared PCs, tangible scale models of the human body or molecules) and workspaces (e.g. tables, boards, play areas), activity completion, etc.,

2.1 SOS Architecture

Figure 1 illustrates the overall logical and physical configuration and structure of the SOS architecture, which includes coordination, *interoperability*, communication, and *visualization / signal-rendering,* modules. The logic modules are distributed on a physical layer composed of several hardware devices (or nodes) that include personal computers (manager), wearable signaling devices (individuals) and stand-alone signaling devices (resources or work areas).

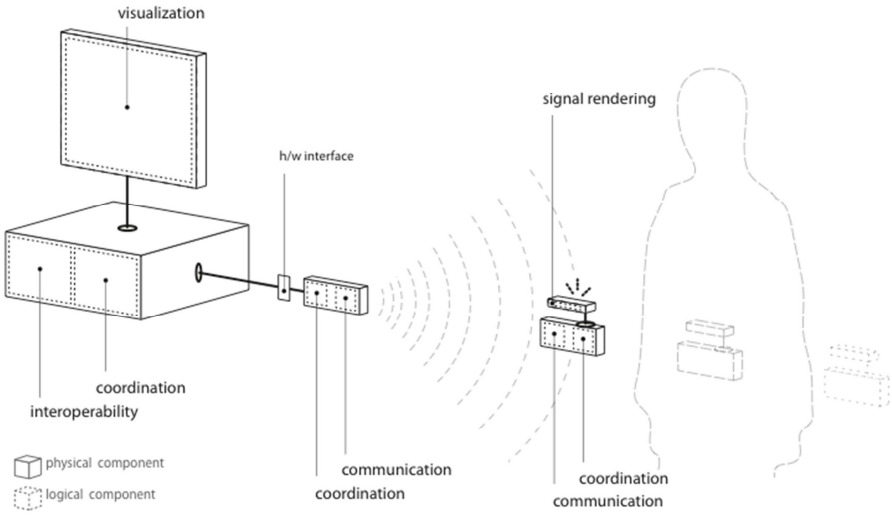


Figure 1: Architecture diagram displaying the corresponding logic modules: the SOS manager on the left sending data to a SOS wearable signaling device

The *coordination* module encapsulates the orchestration logic and provides the mechanisms for modifying (on the fly) and executing the configured orchestration signals. This module provides the capability of associating signals to devices worn by individuals / groups, or attached to resources and workspaces (e.g., color signals denoting group formation and assignment of shared tables should be associated to individuals in groups and to the tables as working spaces). This configuration can be entered manually, (partly) imported from an XML file or via the potential interoperability with digital learning spaces, such as LMS or other educational tools (e.g., Moodle, LAMS, .LRN, CopperCore, etc.). The *interoperability* module is

intended to directly obtain the configuration of some orchestration aspects from those systems, facilitating the extension or continuation of collaborative learning activities from digital to physical spaces - or the other way around (e.g., group formation defined for previous activities supported by an LMS is maintained for the activities performed physically in the classroom, students taking part of different virtual and physical spaces simultaneously). Interoperability with digital spaces can be achieved using different integration approaches [Alario-Hoyos, 10], especially those based on the use of computational languages that enable the specification of collaborative learning flows, such as IMS Learning Design [Hernández-Leo, 07].

The *communication* module is responsible for wirelessly distributing the SOS manager orchestration signals via a radio link to all of the signaling devices connected to the SOS system. The *visualization* module in the manager visualizes the orchestration signals and provides monitoring features to follow progress in the learning flow. In the case of the devices, the *signal-rendering* module renders the signals using physical actuators to make them perceptible to the students and facilitating group awareness. These modules allow teachers and students to be aware of the orchestration at all times and facilitates teachers' coordination of the collaborative dynamic and identifying problems that might arise, such as participants leaving the activity.

2.2 SOS Manager Prototype

The prototype Signal Orchestration Manager instantiates the orchestration logic of the SOS architecture. It includes a graphical user interface (GUI) that allows teachers to configure and modify the orchestration signals to be transmitted to the wearable and fixed signaling devices. The SOS manager communicates through a serial link with the master node that runs specific firmware for sending messages through a hardware transceiver. The transceiver board is based on a JeeNode v4 board, a low-cost Arduino clone that incorporates an ATmega328 microcontroller, a RF transceiver and a USB to serial converter/chip [JeeNode, 11]. In this configuration, each personal wearable device is connected to the orchestration manager trough a radio communication channel and all communication is encapsulated on a transmission layer that handles all data communication between each wearable device and the orchestration manager.

Though the prototype could be considerably improved from the usability perspective, it is operationally fully functional. The manager's GUI can be seen as an activity orchestration editor that provides teachers a view of the available wearable and fixed devices they can configure with (combinations of) colors, blinking and sound signals according to the desired flow of learning activities. As shown in Figure 2, the interface is designed as an open canvas where the devices/nodes worn by individuals are represented as objects. The objects can be added, labeled and grouped together as necessary, by dragging them, reassembling the physical device position in the physical or logic structure of the activity: groups of people, groups of resources, their physical distribution, etc. Each object includes several programmable states that can be configured to a specific signal using simple switches that also serve as indicators for providing a visual representation of the planned orchestration at a glance. The characteristics of the space and the orchestration configuration can be stored in XML digital format and later recovered using the XML file. This promotes

re-use of the configurations, but also enables the mapping of the orchestration configurations with other activity specification formats supported by digital educational spaces, facilitating in this way the (semi-)automatic transition between activities in digital and physical spaces.

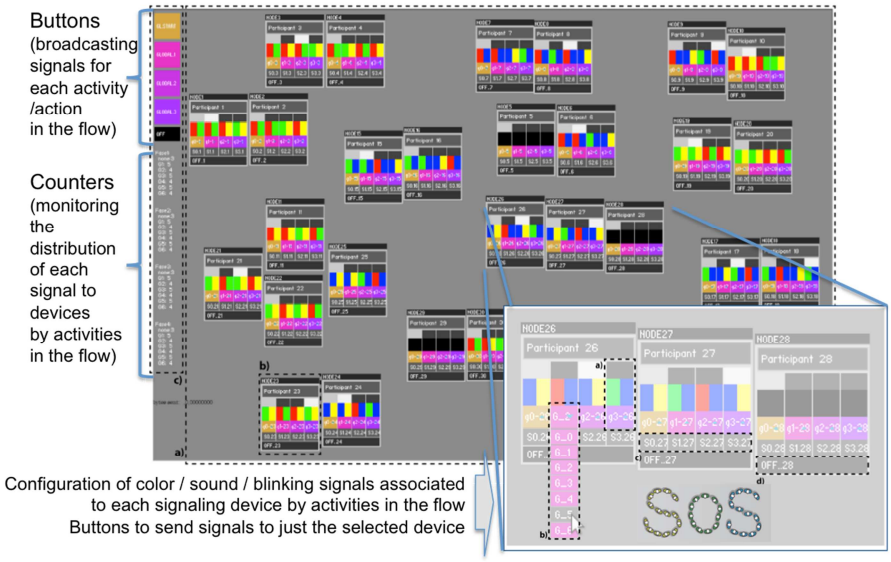


Figure 2: The manager's GUI prototype

Once signals required in a learning flow (or part of them) have been configured or loaded, the initial state can be broadcasted to all of the nodes in order to initialize the activity flow. Each state comprises the set of orchestration signals required by an activity or action within an activity at a particular time. The GUI includes global transmission buttons that trigger the corresponding state for each node. The number of global transmission buttons corresponds to the number of pre-programmable states in the activity (button 1 triggers state 1 of each node, button 2 state 2, and so on), which are typically executed sequentially, but that can be executed at any time if needed. The GUI in each node includes specific transmission buttons that allow the teacher to resend a signal or change it for a particular mode in order to correct conflicts (i.e. new students are assigned to the activity). If desired, these and any signal changes produce an audible signal in the signaling device after the message is received in order to make the user aware of such signal--whether it is a switch-on, a change or a switch-off signal.

2.3 SOS Wearable Signaling Device Prototypes

A set of prototypes of SOS wearable signaling devices has been developed to enable the evaluation of the system in realistic environments. These devices, to be worn by individuals (typically students, but eventually also by other actors), augment the physical target activity with a layer of signals. SOS fixed devices have not been built yet, however they can be easily replaced by paper-prototypes in experiments as

signals for resources and workspaces do not change very dynamically. Of course the availability of devices to attach to resources and spaces would increase the flexibility and scalability potential of the SOS-supported educational scenarios.

The implemented wearable devices are low-cost, and have been designed so that so that they can be used by students at any educational level in the classroom or the playground. In the current prototype, the wearable devices act as slaves of the manager. They incorporate actuators used to display the signals that include luminous and audible indicators capable of engaging the user by directing their attention towards the device itself. Since students have to carry the devices during an educational activity, the devices need to be naturally integrated within the space without interfering with the ongoing activities.

In addition to specific design requirements such as weight, comfort, non-disturbance, visibility for the user and the surrounding participants, and aesthetics, the main design consideration is based on the fact that students have to move through a space or between spaces during learning activities. Thus, the devices have been designed to be as mobile as possible so that students could take them with them wherever they go. Another important consideration in the design of the signaling devices was for the technology not to interfere with the educational activities and for it not to overshadow student-to-student communication. In order to fulfill these requirements, three SOS wearable devices that individuals can attach to their bodies as an everyday clothes or accessory have been iteratively prototyped; a version that hangs on the user's neck, a version that is worn as a belt, and a textile (fabric) version that can be worn as an accessory (see Figures 3 and 4).

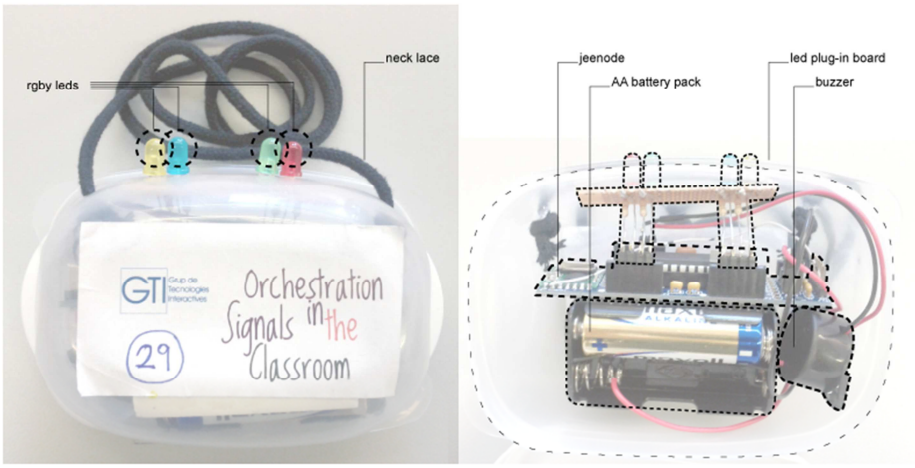


Figure 3: Necklace device: closed on the left, and open on the left.
A Belt design of this device has been also built

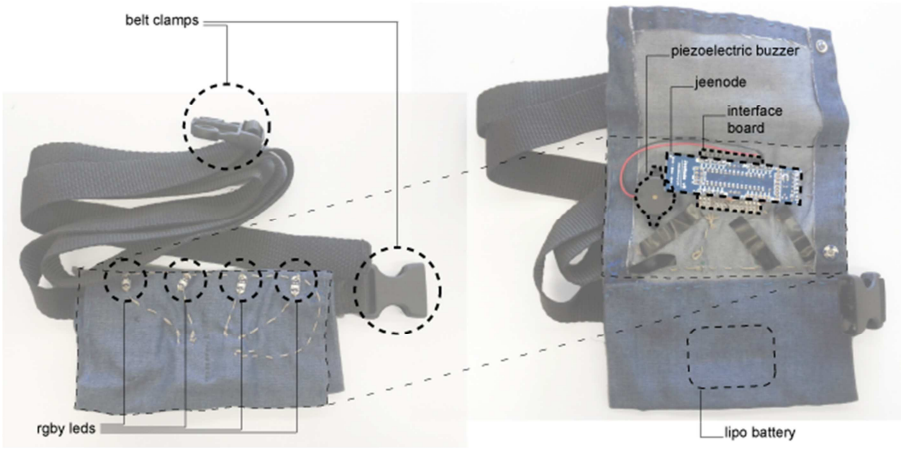


Figure 4: Textile device (as a belt): ready to be worn- on the left, unfold on the right

The wearable devices include the signal-rendering module responsible for enacting the signals received from the SOS manager as visible or audible signals, which potentially require a low cognitive effort for interpreting their meaning. Visual signals display several color combinations associated as configured in the manager to indicate orchestration aspects of the collaborative learning flow, such as group formation. Four LED lights with four different colors (red, green, blue and yellow) provide these signals, which are turned on and off giving different color combinations and blinking options. Auditory signals include various beeping sounds produced by an electric buzzer that signals the start and end of an activity, a change in the activity state, or that device has been properly initialized. The embedded communication module is responsible for handling data exchange between the wearable device and a central SOS manager. The hardware used in the development of the signaling devices is also based on JeeNodes. It includes a transceiver RF12B chip and a microcontroller with EEPROM memory suitable for embedding custom firmware and logic. The transceiver allows the wearable device to be remotely controlled by a central computer, hosting the manager, from up to 100 meters away. The communication firmware interprets the data received from the SOS manager.

The device hardware satisfies key requirements such as low-cost, low-power (long battery life), wearable, and wireless communication. Despite this minimal hardware configuration, it includes the required functional features, such as digital input and output, analog-to-digital converter, and a wireless transceiver. They can be powered using standard or rechargeable batteries (AA, lithium-polimer, etc.) With regards to the physical design, the casing and feedback of the device was designed to be physically and visually unobtrusive so as to minimally disrupt the user's activity - considering the size of the electronics components used in the prototypes. As aforementioned, three prototype versions of the signaling device have been implemented, the first one is a necklace device that hangs in the students neck or that can be wrap around the student's arm, the second one is a belt in which the device is

part of the belt's buckle, and a third one is a textile accessory made out of fabric that can be worn as a belt or band.

The *Necklace* version (see Figure 3) uses low-cost materials that are readily accessible and can be easily replaced. The device's electronic components are packed in a small box that hangs on the student's neck attached to a necklace. The device can be moved and rotated freely around the participants' neck to allow for a better viewing angle, or to share and match their visual indicator to that of their partners. The visual signal indicator is also located on a surface oriented to optimally display the illuminated led lights when seen from above. In the first experiment [Hernández-Leo, 11] students commented on the weight of the device, thus in the *Belt* version of the device a small box with all the electronic components was attached to a belt's buckle. In this second design the students' entire body support its weight, allowing students to move freely and naturally through the space.

The main design consideration for the fabric/textile version of the device is reducing the device size and weight and augment flexibility (see Figure 4) to make it more "socially and culturally acceptable" [Steffen, 09]. This *Textile* device offers a smaller and lighter device that is more flexible and therefore more adaptable to participant's body [Post, 97]. In this new version all the electronic components are sewn inside a fabric bag and most of the electronic connections use conductive thread instead of rigid cables. The device uses surface mount LED lights sewn onto the fabric's visible side that take little space and are as bright as regular LED lights. It uses a Lithium-ion polymer (lipo) battery 2mm thick, which is substantially smaller and lighter than 3 AA batteries (14mm thick). Though this approach could be applied to any piece of clothing, the current prototype has been designed as a belt.

3 Two experiments in realistic collaborative learning situations

In line with a design-based research methodology [Amiel, 08], the conceptualized and prototyped SOS has been iteratively implemented in two experiments framed in real settings where two adaptations of Jigsaw CLFP-based activities are carried out. The aim of the evaluation is to understand the feasibility of the SOS to provide a coordination layer, reflect on the design principles and identify aspects to refine and enhance the solution.

3.1 Evaluation methodology

The experiments are carried out in real contexts, which include many factors such as contextual issues, the characteristics of the students and the teachers, the achievement of educational benefits and the impact of the system. Therefore, mixed evaluation combining qualitative and quantitative data collection instruments is applied [Creswell, 09]. These data are triangulated [Guba, 81] in order to provide a formative evaluation with trustworthy results. The focus for the categories of analysis is narrowed to two main topics: facilitation of the orchestration and usability of the system elements. Quantitative data are considered useful for showing trends around these topics, and qualitative results are used to confirm or reject those trends as well as for understanding them and identifying emergent issues. The applied data collection instruments are shown in Table 1. In each experiment direct observations

are collected by 4 researchers – 2 focused on noting down information regarding timing, and 2 on reporting incidents, use of devices, etc. Quantitative ratings with qualitative explanations and comments are gathered in post-questionnaires with closed and open questions for students. The qualitative opinions of two teacher courses are also collected in questionnaires answered after the experiment.

Source	Type of data	Label
Observations collected during the 1st and 2nd experiments by several researchers	Qualitative observations about timing, evolution of the activity and reactions of the students	[O1] [O2]
Questionnaires completed by the teachers after the 1st and 2nd experiment	Qualitative opinions	[T1] [T2]
Questionnaires completed by the students after the 1st and 2nd experiment	Quantitative ratings and qualitative explanations	[S1] [S2]

Table 1: Data sources for the evaluation, and labels used in the text to quote them

3.2 Context and educational designs

The experiments have been carried out in the context of a master's seminar on Education & Media Communication. A total of 27 students, with 12 different nationalities – 6 men and 21 women, were enrolled in the seminar. Most of them (20) had a media communication or journalism background, 3 are pedagogues, and the remainder had a diverse background. All of them are interested in the educational field, however their use of educational technologies is limited (only 4 have used the Moodle platform, and 1 has used the Blackboard management system). The majority of the students participated in the two experiments, one of them carried out in March 2011 [Hernández-Leo, 11] and the other in May 2011.

The activities proposed for the two experiments use a basic schema similar to the Jigsaw CLFP [Hernández-Leo, 10]. The Jigsaw pattern fosters positive independence (the feeling that team members need each other to succeed) and individual accountability (each student contributes with their fair share) [Aroson, 07]. In particular, this pattern can be used in educational situations where groups of students are required to solve complex problems/tasks that can be easily divided. In its solution, the Jigsaw CLFP proposes to organize the flow of collaborative learning activities according to the following three phases:

- **Initial phase**: Jigsaw Groups are formed in order to collaboratively solve a global problem or task. This task is divided into sub-tasks. Each student in a Jigsaw Group studies a sub-task.
- **Expert phase**: Students having worked on the same sub-task meet, forming Expert Groups, in order to exchange ideas about their sub-problem.
- **Jigsaw phase**: Students of each Jigsaw Group meet again and each member contributes with their expertise in order to solve the global problem.

Table 2 summarizes the educational design of the activity followed in the first experiment. The activity consisted in the collaborative reading of three cases explaining different real scenarios that apply ICT to enhance learning. In contrast to

the pure Jigsaw CLFP, in this design the Jigsaw groups are not formed in the initial phase, what would have fostered a common group identity from the beginning. However, Jigsaw essential characteristics of knowledge distribution in the Initial and Expert phase and interdependent collaboration in the Jigsaw phase are maintained. The cases included a narrative describing the scenarios and a set of questions that students had to answer. Table 2 also specifies the expected number of groups and members as well as the requirements regarding the distribution of resources and spaces in the classroom and, in consequence, the signals needed in order to indicate students the orchestration aspects of the activity. The signals associated to individuals (students) were distributed using the SOS manager, and visualized in the *Necklace* devices. However, the signals needed to identify the cases and the group working areas or spaces were built using color cards (simulating the use of fixed signaling devices), so that they matched the LED colors shown in the devices. Only color signals are used in this experiment (single colors or combinations of two colors). Pictures illustrating the actual enactment of each phase are also provided in the table.

The educational design for the second experiment is summarized in Table 3. The global task proposed to the students was the collaborative reading of the Horizon Report [Johnson, 11], which is structured into three blocks, namely "Time-to-Adoption: One Year or Less", "Time-to-Adoption: Two to Three Years" and "Time-to-Adoption: Four to Five Years". Each block describes a vision of how emerging technologies can have potential impact on teaching and learning in three adoption horizons. In this design only the Jigsaw essence of knowledge distribution in the initial and the expert phases is maintained, having transformed the interdependent activity of the Jigsaw phase into an activity of mutual explanation. The expected number of groups and members as well as the characteristics referring to the distribution of resources and spaces in the classroom are also indicated in Table 3, together with the orchestration signals required. As in the first experiment, the signals associated to individuals were distributed using the SOS manager. However, the three designs of wearable devices were used in this case. The same number of *Necklace*, *Belt* and *Textile* devices were available and they were randomly assigned to the participants at the beginning of the experiment. Again, the signals needed to identify the group work-areas were built using color cards, so that they matched the LED colors lighten by the devices. Three different types of signals were used in this experiment: combinations of colors, sound and blinking lights. The table also includes pictures illustrating the actual enactment of each phase.

Both educational designs represent two different applications of the SOS. They are illustrative examples of how the system can be used to support a considerable number of diverse classroom dynamics - depending on the circumstances of the educational situation, the collaborative learning flow applied [Hernández-Leo, 10], the physical distribution and furniture available in the classroom [Pérez-Sanagustín, 10] and the creativity of the teachers planning the activities. In both cases, the teacher combines the signals with social explanations to present the rationale of the activities or make clarifications about the tasks.

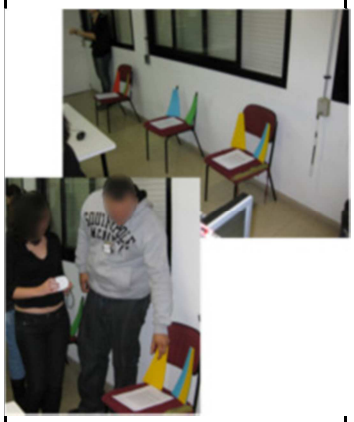
Jigsaw activities carried out in the 1st experiment	Classroom distribution and signal required	Pictures taken during enactment
Initial phase: There are three cases (A, B, C) to read, therefore the Jigsaw groups need to be formed by a minimum of three members. Since 27 students are enrolled in the course, it is expected that 9 students read each case and, therefore, 9 Jigsaw groups can be formed. In this phase each student reads the assigned case (A, B or C) and answers a number of proposed questions about the case.	Since the initial phase is individual, the members of each Jigsaw group do not need to be physically close in the classroom, however they should pick one case (out of three) so that each member of a Jigsaw group reads a different case. ***Orchestration signal***: indicating the case to pick *(same colors)*	
Expert phase: In order to have Expert Groups of a reasonable size, a total of 6 Expert groups are planned (two Expert Groups on the same case, each of them with 4 or 5 students having read the same case). The members of each Expert group meet in order to reflect on the case and discuss their answers to the questions.	Expert groups meet in a specific work area of the classroom so that they are close to each other. These areas should be as much separated as possible from each other. ***Orchestration signal***: indicating expert groups and group working areas *(same colors)*	
Jigsaw phase: The three members of each Jigsaw group meet and compare the cases from the perspective of the proposed questions (which are common to the cases). The group must complete an on-line form with an agreed description of the differences identified in the cases for each question.	Jigsaw groups meet in specific work area of the classroom so that they share a PC and are close to each other. These work areas should be as much separated as possible from other Jigsaw groups. ***Orchestration signal*:** indicating Jigsaw groups and group working areas *(same colors)*	

Table 2: Educational design for the first experiment

The two designs propose the use of color signals to indicate both orchestration aspects. In the two experiments, it is also necessary to specify resources distribution in the individual phase. Color signals are used in the first design, since the resources

are physical artifacts available in the classroom (cases written in pieces of paper). As the working areas, the pieces of papers have associated color cards so that students identify which piece of paper to pick according to the colors visualized in their wearable devices. In the second experiment, the resources (blocks of the report) are digital and have to be accessed via the Moodle LMS, therefore the resources distribution is indicated in the virtual space. In the two designs, the distribution of groups in the expert phase needs to be coherent with the resource distribution accomplished in the first phase. Moreover, in the second educational design, aside from using three different types of wearable devices, the SOS is also used to indicate change of activity and role assignment using sound and blinking light signals.

3.3 Results

The enactment of the experiments, as summarized in Tables 2 and 3, and the analysis of the collected data show that the scenarios were successful in the orchestration of the two Jigsaw collaborative learning flows. The system enabled a distribution of signals to the devices worn by the students, so that students knew automatically which case they should read (Experiments 1, 2), to which group they belong (1, 2), the group working areas (1, 2) (the colors of the cards matched with the group signals received in the devices), change of activity (2), and who was the speaker within the group (2).

As a result, the teachers' orchestration workload decreased as compared to their previous experience of managing similar collaborative processes. Teachers indicated in [T1], "I didn't need to indicate students in every moment what case each of them should read. Students were autonomous identifying their groups…", "During the activity, I can pay more attention to the tasks themselves and not that much to the organization". The teachers support their arguments after the second experiment, "Systems like this are very useful to assist the management of the classroom. I've run similar experiences in the past, and the organization of the classroom demanded a lot of effort from my side. The devices improve this aspect" [T2]. Students also noticed this aspect, "The system may enable to create different dynamics without the need that the teacher is close to you explaining the next step to follow" [S1], "Teachers do not need to give many instructions in the classroom" [S2]. They added interesting comments, "It avoids that the teacher decides compositions of the groups. If a student is not happy in her group, she could not blame the teacher…" [S1], "One of the most positive aspects is that the system decides who is the speaker in each group, in this way nobody can decline playing this role. The system also cared (in the jigsaw phase) about having another person (of the previous expert group) supporting the speaker when explaining the poster to the other students joining the table" [S2]. Interestingly, these orchestration aspects were actually configured in the manager (though automatic orchestration facilities could be implemented) but since the indications were provided by the system, the students attributed the decisions around the organization of the dynamic to the system, and they do not complain or argue them.

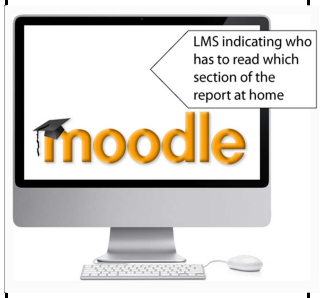
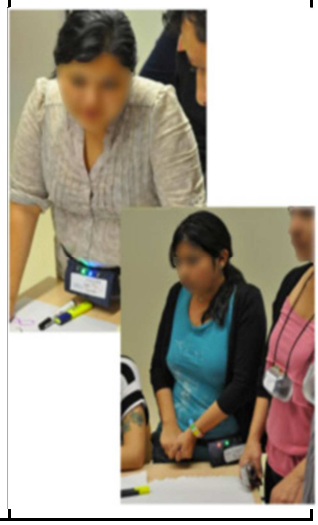
Jigsaw activities carried out in the 2nd experiment	Classroom distribution and signal required	Pictures of the enactment
Initial phase: The report can be divided into three separated blocs. The Jigsaw groups need to be formed by a minimum of three members. Since 27 students are enrolled in the course, it is expected that 9 students read each bloc and, therefore, 9 Jigsaw groups can be formed. In this phase each student reads the assigned bloc.	In the digital space. This initial phase is not performed face-to-face in the classroom. Students are expected to read their bloc at home. To indicate students which bloc they should read (out of the three possible), a list with the names of the students and associations to blocks is provided in the Web space of the course (Moodle). ***Orchestration signal***: no orchestration signal in the physical space required	
Expert phase: Students having read the same block of the paper are proposed to discuss and collaboratively create a poster about their block. In order to have Expert Groups of a reasonable size, a total of 6 Expert groups are planned (two Expert Groups on the same block, each of them with 4 or 5 students having read the same case).	Each expert group meets in a specific work area of the classroom (a shared table). Each space must have the resources needed to create the poster. Since 6 expert groups are planned, 6 collaboration areas with resources are prepared. ***Orchestration signals*:** indicating expert groups and group working areas - resources *(same combination of colors)*, indicating end of phase *(sound)*	
Jigsaw phase: Once the posters have been created, students rotate (**several rounds**) among the tables so as to explain and listen the explanations to the posters. At the end of the activity all the students should have an idea of the main issues discussed in the Horizon Report and be able to complete an individual form with their opinion about the future in Technology-Enhanced Learning.	When rotating among the tables, at least one member of each Expert group should stay in their original table so as to explain the posters to the other students. At the end of the activity all the students should have visited at least two tables with posters on the other two blocks that they have not read. The number of students in each table should be balanced. ***Orchestration signal*:** indicating which table each student should be in every moment *(same combination of colors)*, and indicating who is the speaker *(blinking lights)*	

Table 3: Educational design for the second experiment

In addition to configuring the manager (prior to the activity and on the fly), the orchestration tasks carried out by the teacher were limited to explaining the meaning of the signals, distributing the card signals to specify collaboration areas in the classroom, and indicating the duration of the tasks. That was noticed by the students, "Teachers needed to explain how to interpret the signals in the devices" [S1], and registered by the observers, "A teacher reminds that the student with a blinking signal is the speaker" [O2], "The teacher changes the position of the color cards to indicate the new group working areas" [O1], "The teacher said aloud that the Expert phase finished…" [O1]. When compared to the first experiment, in the second experiment the sound signals were helpful to indicate completion of activities, "In this second situation, students were even more independent thanks to the additional signals used, such as the sound indicating change of activity" [T2]. However, reminding students the duration of the tasks (for their own regulation) was still perceived as an important orchestration tasks that the teachers needed to take care of, "The teacher reminds students that they are expected to complete the activity in 5 minutes" [O2], "I propose adding a timer (with a display) to the devices so that students are aware of the time available / left in each activity" [T2].

84% of the students in the first experiment [S1] and 85% in the second one [S2] rated the SOS system as quite or very useful. Not surprisingly, since the system is mainly supporting the task of the teacher, those students not finding it very useful indicated that the system was not indispensable to carry out the activity or mentioned the risk related to the issue that technology might not always be working [S1, S2]. However, even these students recognized positive effects in using the system, "the same orchestration can be achieved without the system, however its use enables a more organized and faster activity" [S2].

A critical element that led to the successfulness of the orchestration was the flexibility supported by the approach. Despite the unexpected incidents that occurred during the two experiments (summarized in Table 4), teachers were able to re-configure the design of the orchestration transparently to the students. Teachers explicitly said, "The process for sending signals was easy; there was even a student that left the class during the second phase, and it didn't create a problem…" [T1], "The system is very helpful, because it allows me to make changes during the activity in the signals to send…" [T1]. The provided transparent flexibility (for the students) and the decrease in the orchestration workload represent important added values of the approach. The relevance of these values is higher if we think of educational situations with a higher number of students.

Overall, students and teachers highlighted the agile, dynamic and engaging collaboration achieved using the system when compared to their previous experiences (77% of the students experimented similar collaboration situations in the past). This was observed even in the first experiment, when students were using the devices for the first time. As one of the teachers pointed out, "The students get familiar with the device very quickly because it is very easy to use" (T1). In the first experiment many students' opinions were around the dynamicity achieved with the system, "The devices facilitated a rapid group formation", "We kept the rhythm of the dynamics along the whole activity", "The devices open our interest and raise expectations of what will be the next signal" [S1]. This feeling is even stronger in the second experiment, where the observers indicated, "Students organize themselves very fast

according to the signals, and continue working on their tasks" [O2], "Students seem to understand their signals quicker than in the first experiment, and react accordingly" [O2]. Teachers also detected this aspect, "Students are now familiar with the devices and have reacted even faster to the signals" [T2], "I would say that the management of the activity has been even more fluent in this second experiment, students have been more independent with regards to their organization" [T2]. Students' comments are in line with these observations, "Being familiar with the system facilitate its use" [S2], "Since we already knew the system and its reliability, the activity resulted even more organized" [S2]. The timing reported in Table 4 also shows the agile enactment of the activity, where the time devoted to orchestration (despite the unexpected incidents) was considerably low. Students also explicitly mentioned this aspect, "the system enabled an integrated and time-saving orchestration of groups and roles" [S2].

Exp.	**Incidents**	**Actual enactment vs. plan (tables 2, 3)**	**Timing (in mins)**
1st	3 students did not attend **Initial phase,** red light of device 24 did not work, a student read the incorrect case **Expert phase,** a student (that read case A) left **Jigsaw phase,** implications of the previous incidents	1 jigsaw group less than planned, re-distribution of case and group assignments **Initial phase,** Case A was read by 7 students, case B by 9 and case C by 8 **Expert phase,** Expert groups from 2 to 5 members **Jigsaw phase,** Re-arrangement of Jigsaw groups so each group had at least one expert in every case	Presenting the activity: 10 **Initial phase,** Orchestration: 3 Task:12 **Expert phase,** Orchestration: 2 Task:15 **Jigsaw phase,** Orchestration: 1 Task: 20
2nd	**Initial phase,** - digital space - no incidents Physical space: 11 students did not attend, but 4 joined at the last minute **Expert phase,** 3 devices did not work **Jigsaw phase,** a student left	Digital space - as planned Physical space: Complete reconfiguration of the plan in the manager, only 3 expert groups formed **Expert phase,** Devices not working replaced by other devices, changes communicated to the manager via the GUI **Jigsaw phase,** As planned, but in line with the changes performed in the previous phase. The student leaving was not one of the speakers in the groups.	**Initial phase,** at home **Expert phase,** Presenting the f2f activity: 2 Orchestration: 4 Task: 25 **Jigsaw round 1:** Orchestration: 1 Task: 5 **Jigsaw round 2:** Orchestration: 1 Task: 7 **Jigsaw round 3:** Orchestration: 1 Task: 5

Table 4: Actual enactment of the experiments 1 and 2 (as annotated by the observers [O1, O2]*). Orchestration timing includes the manipulation of the SOS manager by the teacher and the students completing the expected action according to the signals rendered in the wearable devices*

Table 5 shows that students were able to see and understand the color and blinking signals rendered by their wearable devices reasonably well. It is worth

mentioning that in the second experiment the color signals were always bi-color, since in the first of experiment it was discovered that the use of mono- and bi-color signals to indicate the same orchestration aspect (e.g., group formation) seemed to be confusing, since some students receiving a mono-color signal were waiting during a brief moment for an eventual second color [Hernández-Leo, 11]. It is also interesting to note that students could see the color signals visualized in the classmates' devices well. However, this aspect needs to be further evaluated in scenarios where it is more critical for the orchestration. Depending on the position of the students in the classroom, the cards indicating working spaces were seen better or worse. In this sense, the furniture distribution of the classroom in the second experiment probably facilitated the perception of some of the visual signals, such as color signals displayed in classmates' devices or the card signals. As one student noted, "the classroom used today is more appropriate for this kind of activity" [S2]. Qualitative observations collected during the experiments, such as "Students identify very quickly their colors" [O1], "All of the students saw the signals almost at the same time" [O1], "Students with blinking signals notice very quickly that they are the speakers" [O2], also support the qualitative data collected in the table. Finally, the sound signal was generally recognized as quite useful, however the sound used is perceived as not quite appropriate, "The sound should be nicer, it was too similar to an alarm that can be associated with something threatening" [S2], "It would be nice that every visual signal conveys an auditory signal, but a pleasing one" [S2].

(out of the four options: very bad, bad, well, very well)	**Exp. 1**	**Exp. 2**
% of students that said that they could see the color signals in their devices *well or very well*	73%	85%
% of students that said that they could see the color signals in their classmates' devices *well or very well*	77%	95%
% of students that said that they could see the blinking light signals in the devices *well or very well*	NA	90%
% of students that said that found *useful or very useful* the sound signals	NA	75%
% of students that said that they could see the "card furniture signals" *well or very well*	77%	95%

Table 5: Main results regarding the signals [S1, S2]

Among the three different physical designs of the signaling wearable devices, the *Textile* version was more popularly preferred. However, each of the designs presented potentials and limitations when compared with the others, and this is probably why some students still preferred the *Belt* or the *Necklace* devices. Table 6 gathers the main results obtained in this respect, which derive from the triangulated analysis of the students' opinions and researchers observations after the second experiment [S2, O2] and, for the case of Necklace device, also after the first experiment [S1, O1] (see also details about first experiment in [Hernández-Leo, 11]).

	Necklace	**Belt**	**Textile**
% of students indicating the most preferred device	20%	30%	50%
% of students indicating the less preferred device	55%	25%	20%
Positive aspects of the devices as indicated by the students	Position of the signals more visible for the person wearing the device and for the other participants. Affordances: it can be also hanged in the hand, in the shoulder...	More comfortable as a belt, easier to wear, freer movement	Lighter and thinner (more compact), aesthetically nicer, brighter color leds
Limitations of the devices as indicated by the students	Considerable size / weight, uncomfortable (object hanging on the neck)	Since it's more comfortable, you may forget to check for color changes	Sometimes difficult to notice in others (too similar to the clothes worn by students)

Table 6: Results regarding the wearable devices physical design [S1, S2, O1, O2]

Interestingly, the 73% of the students after the experiment 1 and the 85% of them after the experiment 2 said that if they were to organize a similar activity, they would like to use the SOS. When asked about what other types of activities they think could be supported by the SOS [S2], they stressed its potential for activities in open spaces beyond the classroom, such as sport classes that involve team formation. They also mentioned activities that require the usage of different (nearby) rooms for small group work, activities where students needs to participate in a certain order or with different forms of participation ("… for example, students with red color signal are expected to make a critique to a statement, students with green colors to provide a justification agreeing with the statement, students with the yellow color to add more examples, etc." [S2]), assessment activities that require a certain control (everybody participates since the group work is being evaluated), and activities involving children (particularly captivated by colors and sounds). Some of them simply said that the system is very useful for any group activity, and especially those involving a high number of students. Teachers also highlighted that the SOS could be useful in spaces outside the classroom, which are typically larger and where it becomes more difficult to directly indicate each student the orchestration aspects. Aside from many diverse collaborative learning flows, the teachers mentioned game dynamics and role rotation activities as scenarios in which the SOS could be applied [T2].

Besides the aforementioned potential extensions to the prototype, such as providing time indications, adding intelligent functionalities to the manager for automating signal configuration or developing the fixed signaling devices for resources and spaces, students and teachers pointed out additional ideas. These ideas include improving the usability of the manager GUI [T2] and enabling students to send signals from the devices to the manager. As they said, "It would be interesting if students could also send signals to the teachers from their devices, for example to indicate that they need help…" [T1] and "A suggestion to improve the system is allowing students to send signals to the teacher in order to volunteer as a speaker, etc." [S2].

4 Conclusions and Future Work

The Signal Orchestration System (SOS) concept, its technological implementation, and the evaluation derived from its iterative integration in real contexts highlight the interest of a technology-supported coordination layer for collaborative classroom (or the like) physical spaces. It addresses practical problems related to the coordination overhead present in collaborative classrooms, while allowing dynamic flexible modifications on the fly and combination with social indications by the teachers. The paper shows how the Signal Orchestration System (SOS) augments physical spaces with digital signals indicating orchestration mechanisms namely, group formation, assignment of group work areas, distribution of resources, role assignment and change of activities. The signals are configured in a manager, according to changing requirements of a specific collaborative learning flow. The SOS will enable further exploration of how this configuration could be also semi-automatically obtained from digital educational spaces such as management systems or task-specific collaborative software tools to facilitate the transition between activities across spaces. The signals are rendered in wearable signaling devices, carried by the participants.

The SOS has been evaluated in a real educational setting carrying out two different scenarios that apply variations of the Jigsaw collaborative learning flow pattern. The main results include:

- The use of the SOS was successful in the orchestration of the two Jigsaw-inspired collaborative learning flows.
- Teachers perceived that the orchestration workload decreases as compared to their previous experiences managing similar collaborative processes.
- The SOS enabled a flexible, agile, dynamic and engaging collaboration.
- The signals rendered by the wearable devices were easily perceived and understood by the students. Each of the physical designs for the devices (out of the three prototypes) presents potentials and limitations when compared to the others.

Lines of future work include improving the usability of the manager's GUI and providing intelligent facilities for the (semi-)automatic configuration of the signals. Another direction is focused on providing a more active interaction between the manager and the devices to enable students to influence in the orchestration process (e.g., students volunteering to play a specific role, indicating completion of activities). Relevant research questions to explore around these lines are: do intelligent facilities

in the manager reduce teachers' orchestration tasks while maintaining (or even improving) the potential effectiveness of the collaborative learning face-to-face situation? How can technology support classroom-orchestrated activities where students also participate in the (on-the-fly) design of the orchestration? A combined use of the SOS with self-organized activities would also be possible if the wearable devices implement context-aware facilities and peer-to-peer architectures, as those explored in [Messeguer, 11; Yang, 06]. The physical design of the devices should be also revised, so that it integrates the advantages of the three designs tested. Moreover, physical designs for the fixed signaling devices to attach to resources and spaces need to be explored. Finally, future research also includes conducting new experiments with different requirements such as, involving other physical spaces (e.g., the playground), exploring the effects of group awareness when compared with other approaches, implementing other collaboration flows, requiring its integration with other digital spaces, putting the scalability of the signals into test, or involving students at different educational levels.

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