

# Let's Jam the Reactable: Peer Learning during Musical Improvisation with a Tabletop Tangible Interface

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There has been little research on how interactions with tabletop and tangible user interfaces (TUIs) by groups of users change over time. In this article we investigate the challenges and opportunities of a tabletop tangible interface based on constructive building blocks. We conduct a long-term lab study of groups of expert musicians improvising with the Reactable, a commercial tabletop TUI for music performance. We examine interaction focusing on *interface*, *tangible*, *musical* and *social* phenomena. Our findings indicate a practice-based learning between peers in situated contexts, and new forms of participation, all of which is facilitated by the Reactable's tangible interface, if compared to traditional musical ensembles. We summarise our findings as a set of design considerations and conclude that construction processes on interactive tabletops favor learning by doing and peer learning, which can inform constructivism approaches to learning with technology.

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## 1. INTRODUCTION

An increasing number of interactive multi-touch and tangible interfaces are being developed to support tabletop group activity and collaboration in diverse contexts such as schools [Cao et al. 2011], museums [Horn et al. 2008; Hornecker 2008], meeting rooms or research labs [Shaer et al. 2010]. A wave of new HCI research has yielded insights into the mechanisms and protocols that people employ in both traditional and interactive tabletop collaboration, which has been used to inform the

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design of interactive tabletops [Hornecker et al. 2008; Marshall et al. 2009; Olson et al. 2011; Scott et al. 2004]. In particular, it has been proposed that interactive tabletops are a useful tool for supporting collaboration and learning in areas such as design planning, humanities, math or science [Dillenbourg and Evans 2011; Harris et al. 2009; Higgins et al. 2011; Horn et al. 2012; Piper and Hollan 2009; Rick et al. 2011; Shaer et al. 2010; Schneider et al. 2012]. However, most studies of tabletop interaction have been one-offs (although see Piper and Hollan [2009] and Wigdor et al. [2007]): either as lab-based evaluations (e.g., Hornecker et al. [2008], Speelpenning et al. [2011]), including relatively structured studies carried out in places such as schools (e.g., Harris et al. [2009]), or observational studies of walk-up-and-use devices in public spaces [Hinrichs and Carpendale 2011; Hornecker 2008; Marshall et al. 2011]. Little work has focused on how groups of users work with tabletop interfaces over time (cf. Shaer and Hornecker [2010]). We thus know little about how to support the development of group coordination and work practices. One reason for that may be that few interactive tabletops described in the literature have sufficient depth or complexity to enable the study of developing expertise in use. In general, most applications are computationally simple, and thus research has arguably focused on the ‘low floor’—the ease of immediate use of tabletop interaction—instead of the ‘high ceiling’ of expert performance.

In this article we describe findings from the video analysis of improvisational sessions of four groups with the Reactable [Jordà 2008], a commercial tabletop and tangible user interface (TUI) for electronic music performance. The Reactable interface is based on tangible building blocks that can be interconnected. The analysis focused on the overarching research question of the challenges and opportunities of using a tabletop TUI based on constructive building blocks over time. In particular, we investigated:

- *Interface characteristics*: how the Reactable interface’s characteristics influence group behaviour over time (e.g., free territory interface or automated connections).
- *Tangible interaction*: what properties of a tangible interface facilitate group progress and development of expertise; the nature of gestures in group tabletop interaction and learning; and the usage of tangible objects.
- *Musical improvisation*: new challenges brought to tabletop musical improvisation compared to traditional ensembles; musical development over time within groups in tabletop musical improvisation.
- *Social factors in the development of expertise*: the nature of collaborative learning through constructive processes on a tabletop TUI; and how can this support different group learning styles.

Studying long-term, unstructured musical improvisation with groups of expert musicians on the Reactable offers an excellent opportunity to investigate group development over time with a novel interface in an unconstrained environment. Previous longitudinal studies of the role of practice in the development of musical skills, such as Sloboda et al. [1996], have tended to focus on traditional musical instruments and individual, classical training. To our knowledge, no long-term study has been conducted on tabletop interfaces and collaboration for an open task such as musical improvisation, although there have been studies of other novel music-related interfaces (e.g., Swift [2012]).

We discovered that the Reactable’s interface promotes group coordination and learning through instrumental interaction in a situated context. It also creates

challenges for group collaboration such as awareness issues or participation roles. We found that the Reactable interface's lack of territorial constraints and its automated connection mechanism (*dynamic patching*) are suitable mechanisms for creative group activities because they promote exploration and creative discovery, which can positively motivate collaborative learning. Our findings are compiled in design considerations for designers, developers, manufacturers, educators, researchers and practitioners. We conclude that a tabletop interface based on constructive building blocks promotes learning by doing and peer learning, which can inform constructivism approaches to learning on computationally enhanced tabletop settings.

This study constitutes the first detailed examination of collaborative learning over time with a tabletop system based on constructive building blocks. We anticipate that it will inform future design and analysis of interactive tabletops. In the next section we summarise previous work on collaboration with interactive tabletops and on musical improvisation that provides the background to this study.

## 2. BACKGROUND

### 2.1 Collaboration with Interactive Tabletops

In this section we consider interactive tabletops, including both touch and tangible interfaces. These are a sub-category of tangible interaction systems, which can combine touch interaction with manipulation of tangible objects on the table. All these types of systems (i.e., only touch, only objects or both) enable users to work over a shared tabletop surface face-to-face. There are numerous studies of the mechanisms and protocols people employ to coordinate their activities around traditional or interactive tabletop collaboration (e.g., Marshall et al. [2009]). These are generally influenced by the task structure (cf. Scott and Carpendale [2010]), and sensitive to the levels of awareness within the group, which are, in turn, affected by the interaction mechanisms used and the interface design [Hornecker et al. 2008].

In traditional tabletop workspaces, Scott and Carpendale [2010] observe that groups in some shared tabletop interaction tasks partitioned space into personal, group and storage territories for, respectively, individual work, shared work or both. Such territories were flexibly adjusted to the task, and opportunistically exploited the available space. Territoriality is often connected with notions of ownership and enforced access rights: Morris et al. [2004] suggest the use of automated coordination policies in interactive tabletops to avoid overlaps and interferences. They observe that these policies provide explicit coordination mechanisms: for example, preventing access to someone else's objects (or territory) unless explicitly granted. However, some researchers question whether such mechanisms might be detrimental to group work. Wang et al. [2006] found that ownership markers increased task completion time and made people feel less part of a group, more uncomfortable and more competitive. Hornecker et al. [2008] discovered that during a planning task on a multi-touch table, groups quickly resolved occasions where one user interfered with the activity of another, and tended to develop collaborative practices that minimised conflict. Both argue that ownership markers and automated territories might interfere with the fluidity of this social negotiation, and might even result in diminished group awareness, as the need for it may be perceived to be less. As the Reactable has no visible partitions or support for personal ownership, since the entire tabletop surface is shared, we here investigate the role of territoriality and ownership.

Several studies investigate how interactive tabletops may support collaboration and learning (e.g., Do-Lenh et al. [2009], Harris et al. [2009], Olson et al. [2011], Rick et al. [2011]), although the potential benefits of tabletop interfaces are still unclear

[Dillenbourg and Evans 2011; Do-Lenh et al. 2009]. Rick et al. [2011] describe how group dynamics determined different styles of collaboration and learning on interactive tabletops, emphasizing the importance of promoting these variations with appropriate tabletop interface design. Harris et al. [2009] found that multi-touch interaction resulted in more task-related talk between 7–8 year old children than a single-touch condition when they carried out a planning task. Olson et al. [2011] found that the use of tangible objects on the tabletop interface (representing a toolbar) reduced conflict and supported coordination. These studies tended to employ interactive tabletops as a medium for learning another conceptual domain (e.g., math or biology). In contrast, we here investigate collaboration and learning in musical improvisation, where the medium for learning is the musical instrument itself, which involves both skill and conceptual learning. Furthermore, the role of verbal communication changes: with music in general, and with musical tabletop interfaces in particular, nonverbal communication is potentially far more prevalent than verbal communication (an exception is Laney et al. [2010]). Thus, analysing the mechanisms by which ideas and approaches are shared can become more difficult. Methods using video help to reveal non-verbal communication: *interaction analysis* [Jordan and Henderson 1995] was used in our study to help understand the role that nonverbal communication played in the development and sharing of ideas between the musicians.

Finally, there are still few studies of long-term use of interactive tabletops (see Piper and Hollan [2009] or Wigdor et al. [2007] for notable exceptions). A study of long-term use of tabletop interfaces may throw light on key aspects of how shared use develops over time.

## 2.2 Musical Improvisation

The spontaneous activity of musical improvisation can be found in most cultures [Bailey 1993; Nettl and Russell 1998], and in different musical styles, genres or traditions from jazz [Monson 1996; Sawyer 2003]; to Indian raga [Viswanathan and Cormack 1998]; Latin dance music [Manuel 1998]; or live coding with laptops [Brown 2006]. The New Harvard Dictionary of Music defines improvisation as “the creation of music in the course of performance” [Nettl 1986, p. 392]. In the history of musicology, improvisation has played a minor role, perhaps because musicologists, influenced by the research traditions of visual art and literature, have tended to concentrate more on the finished works than on the processes that may have led to them [Nettl and Russell 1998]. However, progress has been made in the last decades, with the expansion of ethnomusicological studies and the growth of improvisatory techniques in music education [Bailey 1993; Nettl and Russell 1998].

Musical improvisation can also be seen as a social process, where listening and responding to others are fundamental. This musical practice allows musicians to take decisions freely and spontaneously, and the musical outcome can be rich, varied, and reflect the evolution of the group as a collaborative unit. Pressing [1984, 1988] discusses concepts derived from psychology and neuropsychology: motor control, intuition, creativity and even artificial intelligence. He proposes models to understand the processes of learning and performing that generalise across different cultures.

Even though some studies have focused on communication in music performance [Kawase 2009; Keller 2008; McCaleb 2011], or on the collaborative experience in music [Blaine and Fels 2003], little research has investigated the communication processes and the transmission mechanisms between participants in musical

improvisation. This is an aspect of essential interest for our study. Long-term studies of musical improvisation and communication in traditional contexts exist, such as Seddon [2005] who observes the modes of communication of a traditional jazz ensemble over time, or Healey et al. [2005] who describe the use of space as a key element in the joint performance of a traditional ensemble. However, none relate to communication processes developed over time in novel, shareable interfaces such as musical tabletop TUIs.

Influenced by usability evaluation and CSCW studies, most studies of musical improvisation with novel interfaces tend to be one-offs in labs. Fencott and Bryan-Kinns [2010] focused on public and personal spaces for users of individual computers who accessed a shared virtual representation while co-located in the same room during one session; Bryan-Kinns [2012] studied the distributed use of visual shared representations; or Pugliese et al. [2012] investigated situated interaction and collaboration during mobile group improvisation. Swift [2012] carried out a longer-term lab study that addressed musicians' insights into the experience of co-located improvisation on mobile devices. This study used an ethnographic approach based on field notes, video recordings and post group interviews.

Ethnographic approaches have been used to understand situated interaction and collaboration in musical contexts: Booth and Gurevich [2012] studied collaboration and composition work practices in a real laptop ensemble during three months providing thick descriptions from field notes and video recordings. Although a one-off lab study, Pugliese et al. [2012] also adopted a qualitative approach to understanding collaborative musical improvisation but focused on video analysis of participants' comments when viewing their own videoed session.

In contrast, our approach is based on video analysis of participants' interactions using interaction analysis [Jordan and Henderson 1995]. The study of participants' interactions during unstructured musical improvisation over repeated sessions is thus a new direction in tabletop studies.

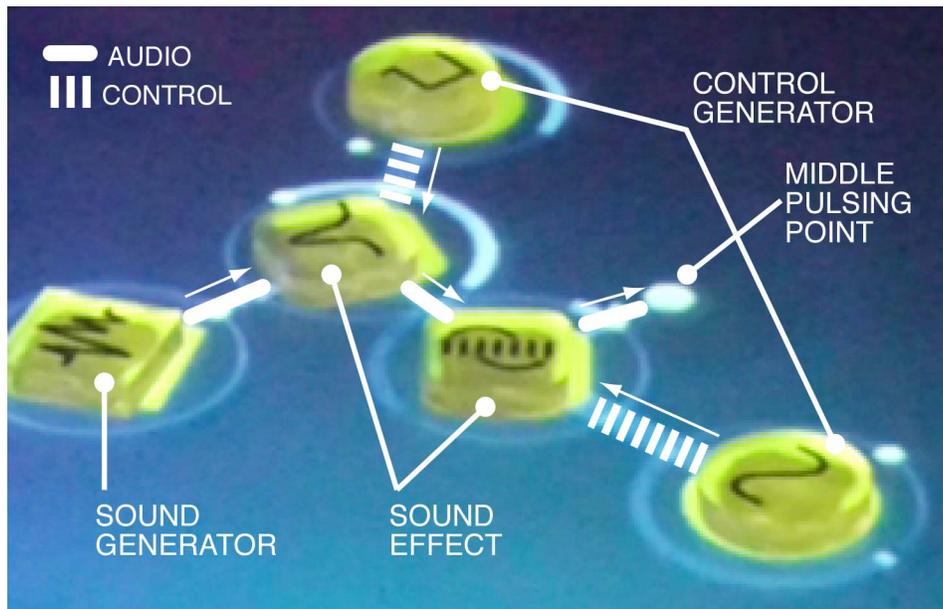


Fig. 1. A Reactable's thread.

### 3. STUDY

In this section we present a detailed account of the study's experimental design and motivate the study design.

#### 3.1 The Reactable

The Reactable is a commercial real-time modular synthesizer [Jordà 2008], which is present in professional music contexts, as well as in public spaces such as museums, science centres and exhibitions. It has a circular tabletop surface (for the experiment we used a Reactable Experience model<sup>1</sup> of 100cm diameter including a rim area of 10cm), and it combines multi-touch input and objects manipulation. The Reactable's TUI promotes constructions with building blocks to producing sound. A set of physical objects allows users to create music by building *audio threads* (see Figure 1), each thread representing an audio channel. These objects have different functions, each represented by different shapes: *sound generators* (squares and cubes), *sound effects* (rounded squares), *control generators* (circles) and *global controls* (polygons). A player's own samples can also be loaded and associated with the different sides of a cube. A white pulsing point in the middle of the surface table area represents the sound output, as well as the tempo of the table. Every audio thread connected to this point is audible and synchronised: they have the same global tempo. Each thread is shown in a different colour from a defined palette, and is built from interconnecting objects. Depending on the object category, each object has a configuration of number of inputs (from none to multiple) and outputs (from none to one), which make the connections between objects possible, and they can be either control signals or audio signals. The sum of the audio threads constitutes a *patch*. A thread needs at minimum a sound generator in order to generate sound<sup>2,3</sup>. Here we will use the terms *thread* and *voice* interchangeably. There is immediate real-time feedback on object recognition on the table, and any change is represented both aurally and visually: while most interaction with the Reactable is realised via the tangible objects, users can use touch input to, for example, mute or unmute the audio connection within a thread. Usually it is possible to change from one to three sound parameters for each object, which are controlled with the rotation angle, the finger on the projected slider on the right side of the object, or the distance to the centre.

The Reactable supports *dynamic patching* in real time [Kaltenbrunner et al. 2004]. This is a significant difference from traditional modular synthesizers and visual programming languages (e.g., PD or Max/MSP cf. Puckette [2002]), because it permits users to edit and play at the same time (build while you play, and play while you build) instead of having two separate modes. Dynamic patching connects the inputs and outputs of sound objects that are close to each other automatically, as if by magnetic attraction (instead of requiring the user to connect objects manually). The Reactable's control complexity combined with a reasonable degree of variability and unpredictability, mean that complex non-linear behaviours can emerge [Jordà 2004], bringing some serendipity that can benefit musical improvisation.

In addition to the influence from analog and digital modular synthesizers (Robert Moog's or Donald Buchla's Voltage-controlled synthesizers), the sound synthesis and

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<sup>1</sup> See: <http://reactable.com/products/experience>.

<sup>2</sup> Video of basic demo showing a sound generator and a sound effect with dynamic patching: <http://www.youtube.com/watch?v=0h-RhyopUmc>.

<sup>3</sup> Video of professional performing the Reactable after several years of training: <http://www.youtube.com/watch?v=kYyg-wVYvbo>.

control method implemented in the Reactable interface can be seen as a physical representation of the unit generator paradigm invented by Max Mathews, and found in MUSIC-N computer music software (e.g., SuperCollider cf. McCartney [2002], PD or Max/MSP cf. Puckette [2002]). The unit generator paradigm consists of unit generators that work as building blocks: they can be interconnected, from basic to complex structures, and produce sound.

The Reactable's interface approach can be seen as an instance of social, hands-on learning using constructive building blocks, an approach influenced by the ideas of Seymour Papert [1980] in the digital domain, and introduced by Montessori [1912] or Fröbel [1887]. A modular building-block structure characterises these educational approaches, which allows creating diverse structures from tangible building blocks. Research in TUIs and education has investigated computationally enhanced tangible building blocks (e.g., Zuckerman et al. [2005]) and shown the suitability of TUIs in education due to its hands-on approach of learning by doing through construction processes, and for promoting group work.

A couple of projects such as Sony Block Jam [Newton-Dunn et al. 2003], or one musical application of Siftables [Merrill et al. 2007], investigate the building of musical structures or musical sequences. Block Jam works as a controller where the input is operated by the tangibles but the output is displayed on a separate screen. Siftables are a multi-purpose platform, which includes a music sequencer<sup>4</sup>, where computationally embedded objects contain input and output that occur in the same place. In contrast, the Reactable incorporates a tabletop surface merging both: the input is operated by the tangibles while the output is projected on them.

### 3.2 Study Design

Our study investigates collaborative learning on a tabletop interface based on constructive building blocks for music performance. While the Reactable is on display in various museums around the world, its primary purpose is to provide expert musicians an expressive instrument for digital musicianship. In museum settings, users tend to be complete novices with the interface and usually also in terms of musicianship, and they rarely gain extended experience with the system. Understanding longer-term use on an expert level necessitated creating a study setting that resembles improvisational sessions by musician groups, while allowing us to capture data. Since our interest is on group progress of both interface apprenticeship and group coordination in musical improvisation, we chose study participants who are not already accomplished Reactable performers.

Our study investigated four groups of co-located musicians collaborating around the Reactable each of them over a series of four sessions, which were scheduled in close succession over the course of one week. Given our participants were already expert musicians with theoretical knowledge of sound generation, this enabled us to observe the initial phase of getting accustomed to the Reactable interface and its rapid appropriation into musical improvisation. All sessions took place in a lab for a controlled environment: video data collection happened in the same place, allowing for control and quality of the collected data for further analysis.

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<sup>4</sup> See: [http://www.ted.com/talks/david\\_merrill\\_demos\\_siftables\\_the\\_smart\\_blocks.html](http://www.ted.com/talks/david_merrill_demos_siftables_the_smart_blocks.html).



Fig. 2. Participants jamming the Reactable.

Despite of the artificial setting, which in essence is a lab study, we attempted to create a casual setup that is close to settings such as rehearsal rooms, where musicians gather together and play (see Figure 2). The lab is located in the music studio area of the Universitat Pompeu Fabra in Barcelona. The room is isolated of the busy classroom areas, and this particular lab has a permanent Reactable in the centre of the room for rehearsals and user studies. The lab has a sound proof door, which is common in recording studios. The room also has two empty desks for occasional soldering of DIY projects (one of the desks has an abandoned PC in the corner), and a cupboard for audiovisual storage. We opted for a dimmed light environment, which is common for rehearsal and performance settings.

### 3.3 Participants

Twelve males aged 22–54 ( $M=32.7$ ,  $SD=7.4$ ) participated in the study, forming four groups: one of two people, two of three people, and one of three to four people (initially three, a fourth joining for the last two sessions). Even though the group members for each group knew each other, they had never played together before. All participants had a medium to substantial degree of musical training, being either music technology students, music practitioners or professional musicians. Of these, 5 were active practitioners of electronic music with synthesizers, electronic devices or computers. Participants were already familiar with the Reactable: 5 participants reported they had “some” familiarity with the technology and how it works, 7 reported themselves as having “a lot” of familiarity. This usually meant some had played the Reactable before, some were introduced through a course, some had the mobile version for smartphones and tablets, and some had watched online tutorials and videos. Only one of the four groups had no experience of using the Reactable: we

named this the beginner group, although its members were still expert musicians. Participants were international (nine from Europe, one from North America and two from South America). In the following,  $G_1$ ,  $G_2$  and  $G_3$  are used to refer to the three Reactable expert groups and  $G_b$  to refer to the Reactable beginner group;  $M_{\#musician}G_{\#group}$  to refer to each of the 12 musicians and  $S_1$  to  $S_4$  to refer to the four successive sessions of each group (e.g., “ $M_1G_1$  in  $S_2$  initiates a new thread” or “shared thread in  $G_bS_4$ ”).

### 3.4 Procedure

Participants could check a printed copy of the Reactable user manual if needed, could stop at any time during the session and were notified one minute before the session end. The set of Reactable objects for this experiment comprised 39 objects: 12 sound generators (SG), 10 sound effects (FX), 10 control generators (CT) and 7 global controls (GL). Of this collection, almost every object was different within the four categories of SGs, FXs, CTs and GLs; although a few of them were repeated (FXs, CTs). All sessions were video recorded with two cameras positioned non-intrusively: one with an overview of the participants around the table and a second giving a more close-up view of interactions occurring on the tabletop surface. An electronic version of the Reactable user manual was sent to the participants the day before their first session. Before each session, participants had the option to load their own samples to be used by sending them to the facilitator.

The facilitator intervened at the beginning and end of each session to set up or shut down the system trying to be as unobtrusive as possible, promoting participants to act as they would in a real context. The aim was to mitigate the Hawthorne effect (cf. Forsyth [2006]). The facilitator moved to a room next to the music lab during the sessions, and only checked on the activity from time to time. Otherwise, participants had complete control of the session: for example, they were told they could stop the cameras if they preferred a shorter session, they could control the audio mixer or turn the output of the speakers up or down at any moment (these were to one side of the Reactable).

### 3.5 Method

We used a qualitative approach to analyse video in detail and identify themes using *interaction analysis* [Jordan and Henderson 1995] based on the two synchronised camera images. Interaction analysis provides an appropriate approach for understanding what people do during practical and object-manipulation related activities, in this case social and tangible interaction with the Reactable. We identified a number of themes: some themes for analysis emerged from iterative analysis of the data, such as interface explorations or peer learning. Other themes partially developed from overarching theoretical questions motivating the research, such as the musical techniques employed. And other themes were inspired by Jordan and Henderson [1995], such as our analysis of beginnings and endings of sessions or of error/repair situations. We utilized Elan<sup>5</sup> to systematically annotate the themes on the videos.

Representative video extracts were repeatedly viewed and discussed in a joined group of three of the authors. We focused on verbal communication and nonverbal communication themes divided into musical, physical or Reactable’s interface-related

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<sup>5</sup> See: <http://www.lat-mpi.eu/tools/elan>, developed by the Max Planck Institute for Psycholinguistics, Nijmegen, The Netherlands [Sloetjes and Wittenburg 2008].

(see Appendix A) as well as on lower level categories around the Reactable's interface-related themes of territories and thread ownership (see Appendix B).

#### 4. GENERAL SESSIONS OVERVIEW

We first give an overview of the sessions and the general group and musicians' behaviours. The sessions lasted from 35 to usually 45 minutes (sometimes even longer): All groups ended up using the full time for their sessions until the room had to be freed.  $G_2$  ( $M_1$  in  $S_4$ ) and  $G_3$  ( $M_1$  and  $M_2$  in  $S_2$ – $S_4$ ,  $M_3$  in  $S_4$ ) loaded their own sounds, whereas  $G_1$  and  $G_b$  only worked with sound synthesis and preloaded samples.

An environment resembling rehearsal music room setting was successfully constructed. Participants manifested enthusiasm to start the session arriving generally on time (sometimes even earlier) for their allocated sessions. There were no comments about whether they studied the manual in-between sessions, but those who loaded their own sounds took extra time to prepare and send them to the facilitator. No one asked to rehearse in-between the sessions: there was little time in-between sessions (usually a day), and the long session seemed to be considered a rehearsal itself. Groups concentrated on the task regardless of the extra furniture of the room, which seemed to go unnoticed.

Group dynamics tended to be as diverse as in a real rehearsal: in  $G_b$ , one participant arrived five minutes after the scheduled time twice, and thus the other duo group member started without him. In  $G_3$  (initially a group of three), a further member joined the group for the last two sessions. Furthermore, there was a generally relaxed and informal atmosphere: In  $G_b$  one musician left the room during a session to attend an urgent phone call whilst the other musician kept playing (see Figure 5); and in all groups musicians approached either the audio mixer or the speakers to turn the speakers' volume level up or down when needed. All groups asked for a copy of the videos of the sessions and  $G_2$  reported that the group would follow-up by meeting and rehearsing together after having played together.

#### 5. FINDINGS: INTERFACE LEVEL

In this section we present the findings at an interface level of the most prominent Reactable's system design characteristics. The shared table space does not provide automatic individual territories, so it can be interpreted as implicit shared manipulation of one musical instrument as well as open self-regulation of individual voices. Another feature characteristic of the Reactable is dynamic patching, the automatic creation of connections between elements based on proximity.

##### 5.1 Territoriality

For behaviours related to territoriality, we assumed imaginary divisions of personal and shared areas according to the number of users and the shape of the tabletop surface (see Figure 3). This approach was inspired by Scott and Carpendale [2010] and Scott et al. [2004] who distinguish between personal territory as a workspace close to the person including storage space, and group territory, such as the centre of the surface table area or the spaces between collaborators (e.g., in the Reactable the global tempo pulsing point and sound output constitutes the centre). While territories assume a spatial distribution of ownership, we had to consider that thread ownership is object-based and may change dynamically as threads change, regardless of the position of the individuals.

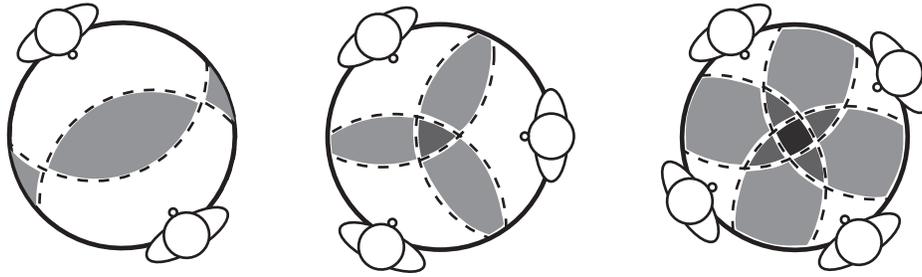


Fig. 3. Imaginary divisions of personal and shared areas.



Fig. 4. A shared thread.



Fig. 5. Dynamic reconfiguration of individual territory.

We devised a number of territory-related themes:

- *Invasions*: ‘Interfering’ in somebody else’s thread via an action.
- *Takes*: Taking an object that ‘belongs’ to somebody else for individual use, which can be *active* (taken from the surface table area) or *passive* (taken from the rim area, where it is not currently used by the other person).
- *Gives*: Handing an object to somebody else for individual use, which can be *active* (given from surface table area) or *passive* (given from rim area).
- *Individual/shared threads*: A thread can belong to an individual (thread built by a single person), or be shared (thread built in collaboration) as shown in Figure 4.

We observed a range of territorial behaviours (*invasions*, *takes/gives* and *individual/shared threads*) related to how the individual and shared spaces were used over time on a free territory interface.

**5.1.1. Individual territories, takes and gives.** Musicians tended to play within the area nearest to them. The bigger the musicians group, the smaller the individual area per person, as shown in Figure 3. These individual areas were reconfigured depending on the number of musicians, as it happened with  $G_3$ , which grew from three musicians ( $S_1$ – $S_2$ ) to four ( $S_3$ – $S_4$ ). In general, musicians finished the session at the same location where they started without switching positions. An exception is the ending of  $S_1$  by  $G_b$ , where  $M_1$  invaded a number of  $M_2$ ’s threads until becoming shared or individual

threads, even moving next to  $M_2$  to fade the volume out of some objects and then remove them. This can be explained as part of the initial exploration of the interface (see next subsection) and the available space when playing in duo. In case someone was missing because he arrived later ( $M_1G_b$  in  $S_2$  and  $S_3$ ) or left for a short period of time ( $M_2G_b$  in  $S_3$ ), the individual area was dynamically reconfigured. Yet, if someone momentarily left his position, but remained in the room (e.g., for manual checking or for changing the speakers' volume level), territories did not change.

An example of reconfiguration of individual territory is shown in Figure 5: nearly the middle of  $S_3$  by  $G_b$ , the surface table area is divided into  $M_1$  and  $M_2$ 's individual spaces. Suddenly, with no verbal exchange,  $M_2$  (musician on the left in frame 1) leaves the room to attend an urgent phone call leaving his threads playing. Then,  $M_1$  (musician on the right in frame 1) interacts with all the threads on the table, fading the volume out of all  $M_2$ 's threads (frame 2), even moving to where  $M_2$  was (frames 3–4). Then  $M_1$  moves back to his original position, and starts two new threads with two cube objects, one of which incorporates a FX from a  $M_2$ 's thread by dynamic patching, and thus his thread occupies part of  $M_2$ 's space. After ca. two minutes,  $M_2$  comes back to the room, goes to his initial tabletop position and asks “How is mine going?”, then  $M_1$  replies “I’ve fade it out”, and  $M_2$  agrees saying “Okay”. Then  $M_1$  moves the cube towards himself making disappear the connection with  $M_2$ 's FX. This example shows how individual spaces and threads are dynamically reconfigured depending on the number of musicians in the room, which contrasts with the exploration of spaces in  $G_bS_1$ .

Before each session, the facilitator organised the objects in the rim area without any specific order, sometimes stacked in pairs because of lack of space. Only  $G_b$  explicitly organised the objects by function and distributed them in the rim area during  $S_1$  with the aim at becoming familiar with the objects, after an initial period of 15–20 minutes of improvisation. Those musicians who loaded cube objects with their own samples tended to have this object close at hand and use it frequently.

Throughout all sessions, musicians tended to play with those objects stored in the rim area nearest to them, although when specific objects were needed, they also took objects from the rim area of others' nearest areas or areas in-between musicians: generally these interactions in others' rim area consisted in choosing an object and using it immediately (passive takes), without asking for permission. Three musicians of different groups ( $M_1G_2$ ,  $M_2G_3$  and  $M_1G_b$ ) extensively did passive takes as part of their repertoire, sometimes leaving the objects again without using them (eventual passive gives). This indicates that the rim area is used as a shared storage area, where the nearest area to oneself is preferred.

How passive takes evolved indicates that the objects and their categories became better known over time. In early sessions they belonged generally to one or two categories: SGs ( $G_3$ ), FXs ( $G_1$ ), SGs and FXs ( $G_2$ ) or SGs and GLs ( $G_b$ ). During the last sessions instead, objects from all categories were chosen, except for  $G_1$  who did not take GLs. This indicates an improved control over the collection of objects. Passive gives were rare: objects were usually stored, after using them, in the nearest rim area to the person, and only sometimes in a fellow musician's rim area when there was lack of space. We rarely observed active takes, which were some intentional and others unintentional: territorial social protocols of personal spaces and objects ownership seem to regulate the use of the surface table area. There were occasional active gives: some of them were handovers (see Figure 9), others happened when moving threads towards others' areas to create free space within one's personal area. The small number of gives indicates that musicians focused on individual threads.

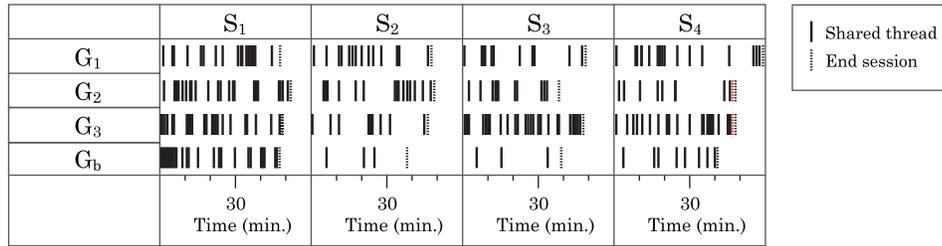


Fig. 6. Timeline visualisation of shared threads for all groups over time.

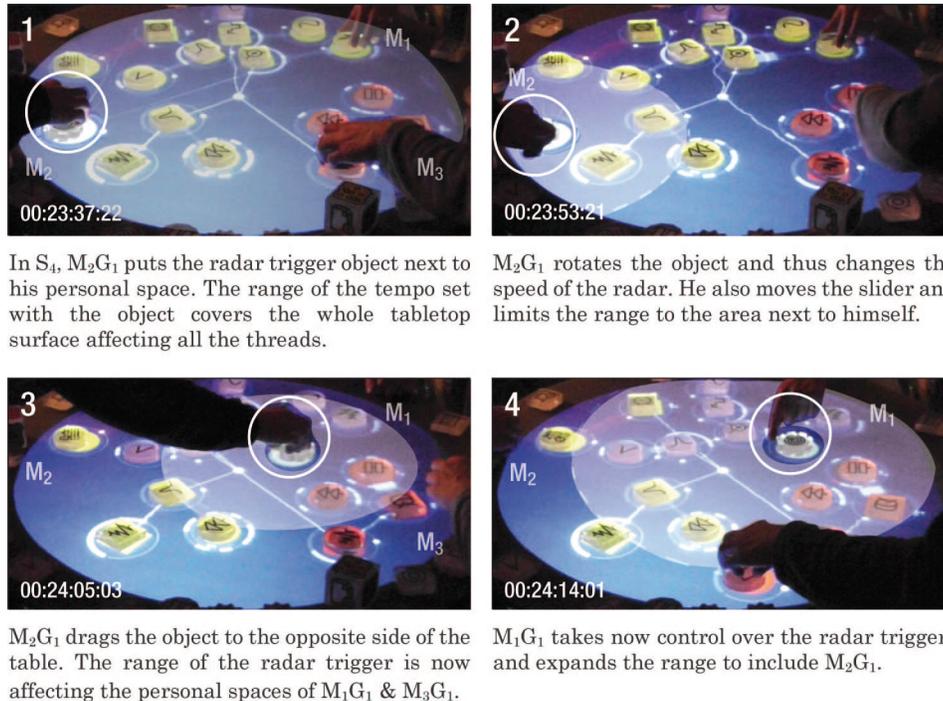


Fig. 7. Sophisticated invasion with the radar trigger object. The radar trigger's area of influence appears shaded, and the circle indicates who is operating the object.

**5.1.2. Thread ownership and shared threads.** As for shared threads (see Figure 6), there is no strong trend apart from sharing more threads in S<sub>1</sub> compared to the rest of sessions (and mainly S<sub>4</sub>). This is probably due to learning to work with the interface. However, only G<sub>1</sub> and G<sub>2</sub> show a progressive decrease over sessions, whereas G<sub>3</sub> increased the number of threads again in S<sub>3</sub> and S<sub>4</sub>. This is possibly because there was a newcomer, and the group necessitated a reconfiguration of the table to four people, and the re-establishment of territories.

The threads tended to be shared by the entire group when they occurred in the spaces in-between musicians or in the middle of the table (for example, see Figure 11, bottom). This indicates the association of the centre and in-between spaces as shared areas. Shared threads were created either intentionally or unintentionally: during early sessions, unintentional shared threads triggered by dynamic patching were rather common (see Section 5.2), whereas in the later sessions participants have learned to control the system, and shared threads were the result of deliberate actions. For example, shared threads were often used as a resource for beginnings or

endings, and their complexity increased in the last sessions, as further explained in Section 7.2.

The change of thread ownership through invasions changed of character over time: Whilst in early sessions invasions were more often a direct intervention into somebody else's thread or a trial-and-error exploration of effects, during the later sessions the interventions were more sophisticated, using objects such as the radar trigger. The radar trigger is a special object that works as a local tempo controller with local up to global effects on all objects in its range. It can influence others threads with no need of physical proximity: the range of the radar can be changed dynamically by moving its slider or moving the object. A representative example of using the radar trigger is shown in Figure 7, which shows a sophisticated invasion of others' threads not necessarily due to physical proximity: it depends on the position of the object, but also on the range of the radar. The smooth and swift change of the range of influence in this example indicates the fuzziness of thread ownership when the effect is not related to physical proximity, raising the question of when an invasion becomes a shared thread because the interferences are continuous instead of discrete. Another example is shown in Figure 14, where the radar trigger is positioned in the centre of the table, affecting individual threads within its range. In both examples, it can simultaneously affect several threads, creating larger shared threads when compared with earlier shared threads.

## 5.2 Dynamic Patching

We found several examples of triggering unintentional effects due to the Reactable's dynamic patching mechanism [Kaltenbrunner et al. 2004]. Unintentional interference with other people's threads, or even the entire patch, was not uncommon, especially during early sessions. Sometimes discerning the functionality of an object was difficult (see Section 7.1 and Section 8.2). If any of these events occurred, the musicians either treated it as a serendipitous event, and integrated it, built on it, or attempted to repair and revoke it. An example of unintentional effects from dragging an object in an early session ( $G_1S_1$ ) is shown in Figure 8 where  $M_3$  (musician on the right) has an individual thread of two objects: a slicer effect (FX) and a SG (frame 1). He drags the FX towards  $M_2$  (musician on the top), this action disconnects the FX from his thread, but no connection is established with  $M_2$ 's threads (frame 2). Then he twice moves the FX towards  $M_1$ 's threads (musician on the left) establishing intermittent connections to two different  $M_1$ 's threads (frame 3 and 4). Finally,  $M_3$  leaves the object in an individual thread of three objects (frame 5). This vignette lasts 15–16 seconds (00:13:37:17–00:13:53:06). Figure 11 (bottom) shows the intentional use instead of dynamic patching and serendipity actions at the ending of a session.

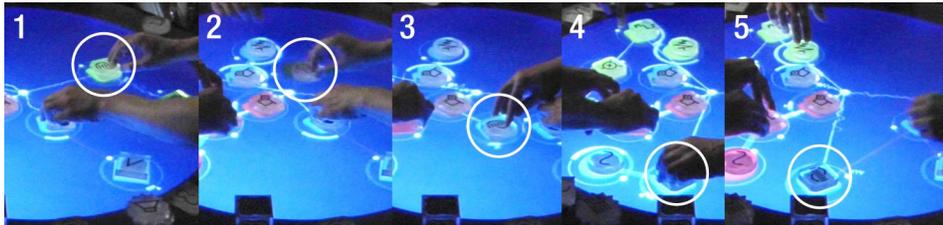


Fig. 8. Dynamic patching.

## 6. FINDINGS: TANGIBLE INTERACTION LEVEL

In this section we present findings at a more generic physical and tangible interaction level, compared to the previous specific Reactable's interface level: interaction control of tangibles over time, gestures, and physical explorations, all of them interactions driven by a tabletop tangible interface.

### 6.1 Development of Control

All groups evolved towards utilising more sophisticated structures and techniques. Groups developed structures from not replicating objects with similar functions in the same thread to replicating them; from linear to non-linear threads; from one single sound effect to a number of sound effects at the end of the thread. Also, groups progressed from using individual techniques, such as dragging, swapping or twisting objects, to combining two of these techniques simultaneously.

Usually threads start with a sound generator (SG) followed by or simultaneously used with other objects. Yet  $G_1$  ( $M_1$  in  $S_1$  and  $S_2$ ,  $M_2$  in  $S_3$  and  $S_4$ ,  $M_3$  in  $S_1$  and  $S_3$ ) and  $G_b$  ( $M_1$  in  $S_3$ ,  $M_2$  in  $S_1$ ) developed preview techniques: musicians first built silent thread structures, and then activated them by adding a SG, which activates the thread. Figure 10 (bottom) illustrates a preview technique used by  $M_1$  in  $S_2$  using two filters, after using this technique with one filter in  $S_1$ :

In  $S_2$ ,  $M_1$  starts building a thread with a resonant filter (FX) in the middle of his individual area, which produces no sound (frame 2). Then he adds a second resonant filter in the space between the first FX and the pulsing dot in the middle of the table, and both objects are repositioned closer to the middle with his left hand, while he adds with his right hand a random control between the first FX and himself. The thread remains with no sound effect. He slightly repositions the first FX and the CT to his left (frame 3). Then he removes the CT (frame 4). After searching among objects nearest to him in the rim area for over 10 seconds,  $M_1$  adds the square wave oscillator (SG), which triggers a filtered sound (thread of three objects).

### 6.2 Gestures

In a study of clarinetists' movements, Wanderley and Vines [2006] used the term *ancillary gestures* for those supporting gestures to the sound-producing gestures. Jensenius et al. [2010] developed this typology of gestures including i) *sound producing gestures*, ii) *ancillary gestures* as support of sound-producing gestures, iii) *communicative gestures* for communication between performers and audience including eye contact, and iv) *sound accompanying gestures* as engaged body gestures not directly related to sound production. We here focus on group movements relevant to tangible and social interaction based on this typology, as a detailed investigation of musicians' gestures is out of the scope of this article.

— *Sound producing gestures*: In our study, sound producing gestures are connected to instrumental interaction, occurring in “activities that crucially involve the manipulation of physical objects” [Jordan and Henderson 1995, p. 65]. We identified instrumental interactions for sound production arising from the manipulation of the tabletop TUI. Sound-producing gestures were generally performed using hand gestures, one or two-handed, with non-exaggerated movements. Yet, there were also occasions of exaggerated movements, for instance

when performing certain techniques such as *strobing* as placing an object on and off the surface table area in a rhythmical or non-rhythmical pattern for a musical effect (e.g.,  $M_2G_2$  in  $S_3$  and  $S_4$  or  $M_4G_3$  in  $S_3$ ). Musicians tended to utilize their whole upper body in this, lifting the tangible object high above the surface while moving their upper body in synchrony, emphasising the rhythm.

- *Ancillary and communicative gestures*: We found that musicians played and coordinated, while focusing their attention on the table surface, with little accompanying verbal communication or direct eye contact. Heads and upper bodies tended to be bent forward, over the table surface. When searching for objects, musicians tended to focus on their nearest rim area, and, if an object was not found, then they would start to look at other parts of the rim area, with slight turns of the head. In all groups throughout sessions, there were no collisions when musicians took objects from others' nearest rim area despite the general lack of verbal communication. An example is a handover shown in Figure 9: In  $G_1S_2$ ,  $M_3$ , playfully exploring effects, moves an object around the table towards  $M_2$ , then he keeps his finger in a pointing gesture on the object, and  $M_2$  takes the object and continues the exploration. Both are looking down at the table surface without any verbal or overt gestural interaction, or establishment of direct eye contact. This demonstrates group awareness in instrumental interaction (cf. Hornecker et al. [2008]), which seems to be facilitated by the shared visibility of the workspace, which in turn is supported by real-time audiovisual feedback. Explicit eye contact during verbal exchanges was mostly observed at beginnings or endings and occasionally in-between sessions (see Section 8.2). Occasional establishment of eye contact can be determined in the video overview from participants' lifting their heads. This is consistent with observations from our prior studies of tabletop interaction. Sometimes it was combined with actions that indicated engagement at the end of a session such as laughter in all groups throughout all sessions, including shaking hands in  $G_1S_1$  or clapping hands in  $G_2S_1$ .
- *Sound accompanying gestures*: Some groups showed more sound accompanying gestures than others. This indicates a connection between gestural interaction and group dynamics. These gestures were generally related to body movements. In  $G_1$ , participants remained motionless with occasional shift of upper body towards the table surface when manipulating objects. In  $G_2$ , all participants appeared to be highly engaged, often bobbing their heads and occasionally dancing in synch with the music with the whole upper body. *Bobbing* may support the musician's sense of rhythm, and also may serve to synchronise the group in this rhythm. In  $G_3$ , participants occasionally shifted their upper bodies towards the table surface to manipulate objects, and often nodded their heads. In  $G_b$ , participants remained motionless with occasional shift of upper body towards the table surface for object manipulation and also sway changes from left to right. In contrast with traditional ensembles, there were few overt gestures to help synchronise the group: a synched, shared interface seems to support this.



In  $S_2$ ,  $M_3G_1$  drags a resonant filter towards  $M_2G_1$ 's area while playing with the serendipity of dynamic patching (frame 1).  $M_3G_1$  stops with one finger on top of the object.  $M_2G_1$  approaches his hand and takes the object: Handover (frame 2).  $M_2G_1$  keeps dragging the resonant filter on the other side of the table (frame 3).

Fig. 9. Handover.

### 6.3 Explorations

We noticed several situations where groups explored the limits of the musical interface, such as adding all the available objects to the surface ( $G_3$  in  $S_2$ – $S_4$ ), stacking objects as a unity ( $M_1$  and  $M_3$  in  $G_3S_2$ ), rolling or tossing objects ( $M_1$  in  $G_1S_4$ ), or adding a mobile phone on the surface as an alternative object with obviously no sound effect ( $M_3$  in  $G_3S_4$ ). An example of these explorations happens in  $G_1S_4$  when  $M_1$  is making a circular object roll towards the middle of the table, eventually letting it fall down either side. This exemplifies an explorative dialogue between the physical affordances of an object (e.g., rolling a circular object) and the digital interface (see Figure 11, bottom, frame 2).

## 7. FINDINGS: MUSICAL LEVEL

In this section, we detail the findings of tabletop musical improvisation over time at both individual and group level. We here focus on the musical elements employed by the groups over the course of sessions. It was out of the scope of this article to consider the music style of the groups, their progress, and the quality thereof.

### 7.1 Individual Level

Video data revealed that awareness issues mainly arose in the initial sessions, where musicians had difficulties in understanding particular features of the interface, for example, misusing the programmer object. This object can only reprogram the samples of a number of SGs (i.e., the cubes and the instruments), but has visual feedback with any object. On a number of occasions, musicians used this object in the wrong context with no apparent acoustic or visual clue (e.g.,  $G_1$  and  $G_2$ ). Despite occasional difficulties, groups also showed an increasing ability to cope with the Reactable's lack of sound preview (there were no headphones or other alternatives for pre-listening to the sound), as exemplified in Figure 10 (bottom) and detailed in Section 6.1.

We observed a number of solos (i.e., leading voices), which increased in sophistication over time, in all four groups. Yet some groups were more inclined to perform solos (e.g.,  $G_3$  and  $G_b$ ) than others. Some solos were built up to an existing accompaniment and some triggered dialogues (as detailed in the next section). There were individual musical explorations: a subset of these was mimicked and further developed by other peers as explained in Section 8.1, whilst some were overtly developed individually such as creating serendipity threads with numerous objects ( $M_2G_3$  in  $S_1$  and  $S_2$ ), or dragging an isolated object along different threads in an exploratory mode ( $M_3$  in  $S_1$ – $S_4$ ).

Occasionally a group member would stop for several seconds or minutes and contemplate the patch, leaving his individual space with an active thread, but sometimes with none (e.g.,  $M_1G_1$  in  $S_4$ ,  $M_2G_1$  in  $S_2$ – $S_4$ ,  $M_2G_3$  in  $S_1$ – $S_4$ ,  $M_3G_3$  in  $S_1$ – $S_4$ ,  $M_4G_3$  in  $S_4$ ).

## 7.2 Group Level

We found egalitarian participation and no evidence of fixed musical roles. The configuration of the objects and thus the resultant musical output changed constantly. Distribution of roles was dynamic and tended to happen nonverbally: we only found an occasional explicit distribution of musical roles with  $G_b$  (e.g., melody vs. rhythm). In general, there were tacit leading voices in all groups (e.g., solos vs. accompaniment or conversation of melodic voices). These voices were dynamically exchanged as detailed below (e.g., dialogues, intros vs. endings).

Jazz musicians describe musical improvisation as a conversation between two or more musicians, mediated by open-ended turn-taking [Monson 1996]. We identified a number of dialogues between musicians. Our analysis looked at the nature of these dialogues based on dichotomies such as homophonic vs. heterophonic, and elements of musical forms such as call-response or rhythm vs. melody (cf. Pressing [1984, 1988]). Over time, these dialogues became more complex and sophisticated, using more variations in tempo and heterophonic voices. For each group, we examined one video extract of a basic dialogue (which tended to happen in early sessions) vs. one of a complex dialogue (which tended to happen in last sessions). Results are detailed in Table I, where we can see a range of leading roles.

Table I. Basic vs. complex dialogues

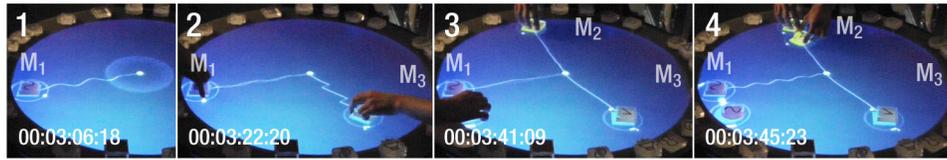
Groups	Basic Dialogue	Complex Dialogue
$G_1$	In $S_1$ sequential call-response with two textured, melodic voices ( $M_2$ , $M_3$ ) and with one fixed rhythm voice ( $M_1$ ). There is lack of role change or variations in tempo. The three voices are clearly heard.	In $S_1$ the leading melodic voice is transferred from $M_2$ to $M_1$ (dynamic role change). The other two voices ( $M_2$ , $M_3$ ), which are rhythmic melodies, add counterpoint to the leading melody as call-response. There are several variations in tempo. The three voices intertwine with one another.
$G_2$	In $S_2$ two simultaneous leading melodic voices (i.e., $M_2$ as high pitch voice, $M_3$ as mid-pitch voice), and a bass/rhythmic voice ( $M_1$ ). There is lack of gradual changes in volume. The three voices add counterpoint to one another.	In $S_3$ there is <i>crescendo</i> or a gradual change in volume with one leading mid-pitch melodic voice ( $M_2$ ), one secondary high pitch melodic voice ( $M_1$ ), and a subtle bass/rhythmic voice ( $M_3$ ). $M_1$ and $M_3$ add counterpoint to $M_2$ .
$G_3$	In $S_1$ sequential call-response with one call high pitch melodic voice ( $M_3$ ) and two response melodic voices (i.e., $M_1$ as mid-high pitch and $M_2$ as mid-low pitch). All voices combine serendipitously (e.g., serendipitous tones or rhythms).	In $S_3$ two simultaneous melodic voices, one high pitch ( $M_1$ ) and one low pitch ( $M_2$ ), which combine harmonically and rhythmically, instead of serendipitously.
$G_b$	In $S_2$ two simultaneous high pitch melodic voices ( $M_1$ and $M_2$ ) combined with a homophonic bass/rhythmic voice ( $M_3$ ). All voices combine serendipitously (e.g. serendipitous tones or rhythms).	In $S_4$ the leading melodic voice is transferred from $M_2$ to $M_1$ (dynamic role change): first, simultaneous one high pitch melodic leading voice ( $M_2$ ) combined with a low pitch melodic voice ( $M_1$ ); second, simultaneous one high pitch melodic leading voice ( $M_1$ ) combined with a low pitch melodic voice ( $M_2$ ). All voices combine harmonically and rhythmically, instead of serendipitously.

Given the time constraints on a musical improvisation session and the protocols of improvisation, participants had to coordinate what in popular and jazz music is traditionally known as intro and ending. In interaction analysis [Jordan and Henderson 1995], beginnings and endings are considered meaningful units when analysing an activity as a structured sequence of events. During intros, musicians tended to focus more on their individual voices using more sophisticated structures, although there were also invasions and shared threads in spaces mainly in-between musicians. For endings, we found that musicians in some groups tended to share voices in a more sophisticated way ( $G_1$ ,  $G_3$  and  $G_b$ ), frequently using the middle of the table. When comparing groups and sessions, we found a large variety of types of endings, with various combinations of the same set of elements (see Table II), illustrating how group dynamics may differ even in a small set. Figure 10 illustrates the first and last intro of  $G_1$ , whereas Figure 11 illustrates the first and last ending of  $G_1$ . Both indicate how musically sophisticated intros and endings can become over time: For example, in intros (Figure 10) sophistication is shown from using one SG per thread with immediate sound output (top) to using more objects per thread including the programmer for reprogramming the samples of a cube object or the use of the preview technique for controlling when to trigger the sound output (bottom). In endings (Figure 11), sophistication is shown from sequential removal of objects of individual threads (top) to voluntary serendipitous contributions to a large shared thread on the centre of the table (bottom).

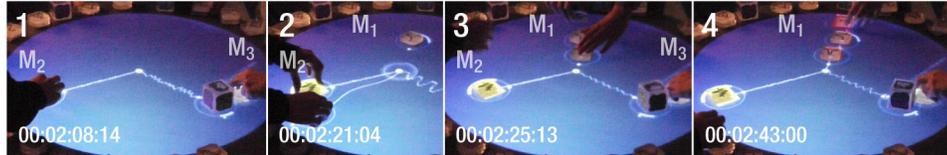
Table II. Endings. The icons within the circle represent the different types of ending techniques that were utilised. Filled icons indicate the actual use of this technique in a session

Group	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	S <sub>4</sub>
$G_1$				
$G_2$				
$G_3$				
$G_b$				

- ▶ *Fade out*: Incremental decrease of the volume (e.g., using global volume or modifying the volume parameter of a SG).
- ◆ *Global object*: Use of an object with global effect (e.g., global feedback, global volume, global tempo, panning, radar trigger).
- *Objects removed sequentially*: Starting from one or multiple threads for each musician to objects removed one after the other.
- *Serendipity*: Presence of serendipity actions (e.g., massive use of all the objects or randomly tossing an object).
- ★ *Shared threads*: Presence at some point of a shared thread (e.g., starting from one thread for each musician to one shared thread).

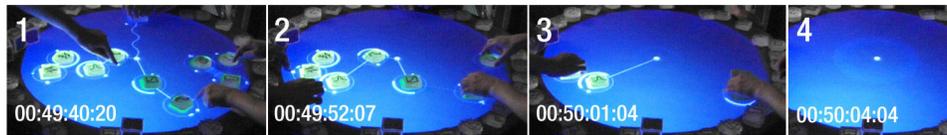


In  $S_1$ ,  $M_1G_1$  adds a first SG (frame 1).  $M_3G_1$  adds and rotates a second SG whilst  $M_1G_1$  changes the slider of the first SG (frame 2).  $M_2G_1$  adds and rotates a third SG whilst  $M_1G_1$  adds a controller to the first SG (frame 3).  $M_2G_1$  adds a filter to the third SG while rotating both objects (frame 4).

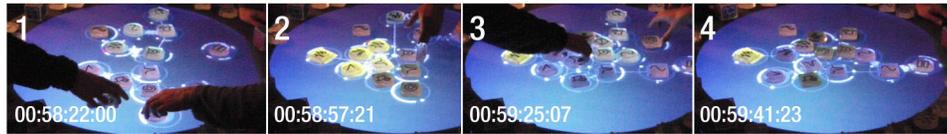


In  $S_4$ ,  $M_3G_1$  adds a cube and a programmer to select a sample and  $M_2G_1$  adds a SG (frame 1).  $M_2G_1$  adds a second SG and rotates one with each hand while  $M_1G_1$  adds a FX (preview technique) (frame 2).  $M_3G_1$  reprograms the cube,  $M_2G_1$  removes the second SG and  $M_1G_1$  adds two more FXs (preview technique) (frame 3).  $M_1G_1$  removes one of the FXs and adds a SG for the thread to sound (frame 4).

Fig. 10. Basic (top) vs. complex (bottom) intro.



In  $G_1S_1$ , each musician is in charge of one thread (frame 1). They respectively start removing their threads (frame 2). They keep removing their threads (frame 3) ... generating silence (frame 4).



In  $G_1S_4$ , There is a shared thread in the centre that musicians playfully contribute to (frame 1-3) ... until the patch is left "alive" (frame 4).

Fig. 11. Basic (top) vs. complex (bottom) ending.

## 8. FINDINGS: SOCIAL GROUP LEVEL

In this section, we detail the results of social group interaction in terms of mimicking behaviours and verbal communication.

### 8.1 Mimicking

Mimicking refers to group members imitating another's actions or behaviours. Mimicking occurred in all groups and throughout all sessions with no explicit talk. We noted that musicians generally tended not to look up at each other, and seemed to rely on peripheral vision even when actions were imitated close in time. However, during active manipulation and problem solving, if engaged in intense discussion, participants looked onto the shared workspace combined with glances at each other: for example, in response to a joke or an observation.

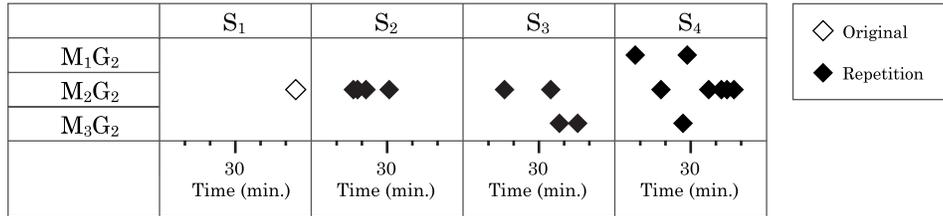
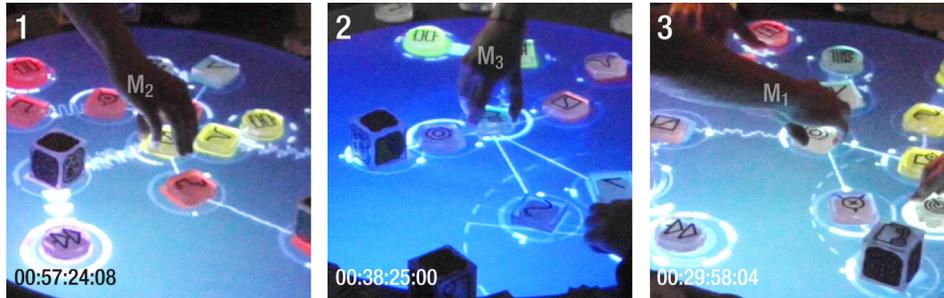


Fig. 12. Timeline visualisation of mimicking one technique over time.

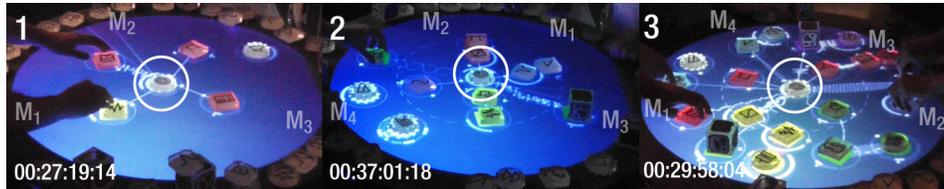


In S<sub>1</sub>, M<sub>2</sub>G<sub>2</sub> operates distortion effect in the centre using strobing and twisting.

In S<sub>3</sub>, M<sub>3</sub>G<sub>2</sub> operates global feedback in the centre using strobing, twisting & dragging.

In S<sub>4</sub>, M<sub>1</sub>G<sub>2</sub> operates granular effect in the centre twisting and holding for 90 sec.

Fig. 13. Mimicking.



In S<sub>2</sub>, discovery of using the radar trigger object as a 4-step sequencer (frame 1). In S<sub>3</sub>, reuse of the radar trigger technique as a 4-step sequencer (frame 2). In S<sub>4</sub>, again, reuse of the radar trigger technique (frame 3).

Fig. 14. Explicit peer learning.

Generally, in early sessions, musicians tended to mimic basic structures or techniques: for example, muting or unmuting a thread (G<sub>1</sub>S<sub>1</sub>), strobing on and off whilst twisting left and right a filter positioned at the end of the thread (G<sub>2</sub>S<sub>1</sub>), exploring and dragging an object on different threads (G<sub>3</sub>S<sub>1</sub>), or piling objects of same shape (G<sub>3</sub>S<sub>2</sub>). By contrast, during the last sessions, musicians tended to mimic more complex structures or techniques, e.g. building the same complex structure such as a CT connected to a SG connected in sequence to two FXs (G<sub>1</sub>S<sub>3</sub>); twisting a FX affecting a SG (G<sub>2</sub>S<sub>3</sub>); operating two SGs simultaneously (G<sub>3</sub>S<sub>3</sub>); or shaking two FXs between two threads (G<sub>3</sub>S<sub>3</sub>).

We identified repetitions of different techniques among groups and sessions. A representative example of how an idea is initially used by one musician, and then repeated and reshaped by the rest of the group, is represented in Figure 12. Here, M<sub>2</sub>G<sub>2</sub> discovers and develops in S<sub>1</sub> and S<sub>2</sub> the technique of strobing on and off and

twisting left/right an object (generally used with FXs or the global feedback object) pointing to the white pulsing point in the centre, which modifies the general sound output and tempo. In  $S_3$ , not only  $M_2$ , but also  $M_3$  adds the technique to his repertoire. Finally, in  $S_4$ ,  $M_1$  also integrates this technique, together with  $M_2$  and  $M_3$ , who keep using it. Figure 13 illustrates the use of the technique by each of the three participants throughout sessions.

## 8.2 Verbal Communication

Conversations happened mostly at the beginnings and endings of the sessions, and occasionally in the middle. Verbal communication was primarily used for sharing knowledge in explicit peer learning. The most common events were error/repair situations, discoveries, question/answer situations, thinking alouds, or group discussions. It also was used for sharing expressions of satisfaction.

A representative error/repair situation, which happened in all groups, was the use of global volume. This object controls the global volume of the Reactable by rotating the object, and it also has a slider, which defines the amount of reverb or echo. The reverb feature is not explained in the user manual, though. In several occasions, by just rotating the object, the reverb situated unexpectedly at its maximum value. In all groups it took a certain time, either in the same session, or in the following sessions, to understand the behaviour of this object, and thus to learn how to repair reverb situations arising from the use of global volume. In general, this issue was resolved individually (e.g., by trial and error), and then the knowledge was shared with the group by explicit communication. We here give one example:

In  $G_1$ , the issue appeared and was repaired in  $S_3$ .  $M_2G_1$  started the reverb situation, and right after he repaired the situation by moving the slider. Later on,  $M_2G_1$  used it again with control. After the ending,  $M_2G_1$  shared his discovery by having a group discussion with  $M_1G_1$  and  $M_3G_1$  about the behaviour of the object.

There were also examples of verbal communication in group-specific situations. In  $G_3S_2$ , the group of three discovered how the radar trigger object worked as a metronome (set to 4/4) when positioning the object to the centre of the table together with four more objects located in each quarter of the radar's range and representing one thread each. The group discovered the object's possibilities by discussing and doing (see Figure 14). The group remembered and re-used this technique in the following sessions when they were four musicians ( $S_3$  and  $S_4$ ), using more objects and threads. The technique was named "the sync" in  $S_3$  by  $M_3G_3$  ("Let's try to do the sync"), and so when the new member started in  $S_3$ , he was instructed by doing and with explicit explanations, for example,  $M_3G_3$  explained to  $M_4G_3$ : "This is like a four-step sequencer, this is time 1, 2, 3, 4" pointing to the four quarters.

## 9. DISCUSSION

Here we discuss the findings of interface, tangible, musical and social phenomena. Then we outline design considerations, study implications, limitations and future work.

### 9.1 Reactable's Interface

The observed division into personal and shared spaces concurs with the territorial behaviours found by Scott and Carpendale [2010] and Scott et al. [2004] in conventional tabletop collaboration. Our findings of musicians tending to play with

the objects nearest to themselves also agree with their observation that the spatial location of resources influences the perceived ownership. The storage territory of the rim area had a shared use, a behaviour that happens, as described by Scott and Carpendale [2010], when the storage territory is located in the group territory, in this case a rim area visible to all. Accordingly, an open question is whether there would be more reservation and organization of resources with auxiliary storage territories.

Our data indicates that territorial constraints might be harmful for group dynamics (cf. Scott and Carpendale [2010], Scott et al. [2004]) in case of tabletop free improvisation activities, where it might potentially interfere with the early exploratory behaviour that musicians utilised to understand the effects of different objects and manipulations. In addition, once the initial phase of exploration was completed, invasions into other musicians supposed territory or threads tended to have a clear musical purpose and were not objected to or rejected by the other group members. This agrees with Hornecker et al. [2008] in allowing for interventions into others' spaces to occur as a mechanism that promotes a rich range of opportunities for collaborative work, group dynamics, and expertise development.

Objects with different levels of thread influence ranging from local to global seem to encourage a multiplicity of interventions to others' spaces (e.g., radar trigger). This contrasts with traditional instruments where there is usually a physical boundary between group members as well as instruments, which in itself operates as a territorial indicator. Thus, a tabletop TUI with lack of territorial constraints, as is possible with the Reactable, raises new approaches to group collaboration in creative activities such as musical improvisation. It is uncertain whether it would be helpful for efficiency-based activities though.

Our findings suggest that Reactable's dynamic patching of automatic connections promotes serendipity and creative discovery, a mechanism that seems useful for creative domains in tabletop TUIs, especially during early exploratory phases. Although this approach eases access and use for beginners and casual users, it can also be interpreted as a constraint because the automated decision of connectivity does not allow for full manual control. An additional mechanism for manually consolidating the connections would be useful and suitable for advanced users who tend to prefer having full control of the interface [Blaine and Fels 2003].

## 9.2 Tangible Interaction

The Reactable interface is designed on a modular and constructive basis [Jordà 2008]: a set of tangible building blocks, with a specific function each that can be interconnected creating from basic to complex configurations, provides a modular interface. Modularity is mentioned as a design feature for learning through construction processes with TUIs [Zuckerman et al. 2005]. Nonetheless, a large collection of building blocks might become difficult to manage on a tabletop surface due to its space limitation, which reduces the ultimate level of complexity compared to other modular systems with fewer restrictions on space (e.g., LEGO bricks or virtual simulations of modular structures). Thus, an open question is how to keep this modular approach within the space restriction of a tabletop surface, which limits the potential level of complexity. For example the Reactable's circular shape limits the space available, and only operates with two-dimensionally positioned objects. These limitations might begin to be noticed after several days of practice, yet virtual mechanisms may counterbalance this physical limitation by providing complex and non-linear behaviours at a digital level, as it happens with the Reactable's dynamic patching mechanism.

Body and hand movements are characteristic in tangible and physical interaction. With the Reactable, groups performed a range of bodily actions and hand gestures, for example, sound producing gestures, ancillary gestures, communicative gestures, or sound accompanying gestures (cf. Wanderley and Vines [2006], Jensenius et al. [2010]), with generally little eye contact and individuals' focus on the tabletop surface. Such lack of eye contact has also been found in past studies of group tabletop interaction [Hornecker et al. 2008] and recalls early research on video conferencing systems, which revealed that visibility of the workspace is often more important for awareness and collaboration than 'talking heads' video [Nardi et al. 1995]. The observed bodily coordinated actions between users (e.g., handovers or bobbing heads in synch) seem to be promoted by interface mechanisms such as synched multi-threading (i.e., using the same system time clock for all tangibles' connections), as well as a shared interface with real-time feedback where manipulation and feedback response occur at the same space and time. This synchronicity of the input and output (real-time feedback) is suggested as a design feature for learning in a constructive process with TUIs so there are immediate results from actions [Zuckerman et al. 2005]. Our study found that the Reactable encouraged bodily interaction (e.g., head bobbing) with music because it affords standing and facing the other musicians. With touch-based mobile devices, instead, there is less need to interact with the body, and interactions are of smaller scale, thus the joint action is of a different character and appears much more introverted (cf. Swift [2012]). This recalls Jordà's [2008] description of the Reactable's design purpose of increasing performativity in electronic music making.

We could also see how the tangible objects support performative action, for example in the strobing effect, where musicians tend to lift the object high up from the service to then almost smack it down again, in a full-body movement that emphasises the rhythm. While we have not explicitly focused on this in our analysis, some of the examples we reported demonstrate how the use of tangible objects as sound manipulators supports ancillary and communicative gestures. For example, the participant moving a sound effect object across the table towards another musician leaves his finger in a pointing gesture on it. Touching the object does not yet manipulate it, whereas purely touch-based interaction suffers from the Midas-touch problem. As the literature on the Reactable's development highlights [Jordà 2008], manipulation if compared to touch can free musicians visual attention to focus, for example, on other objects, or watching what his/her peers are doing on the table surface while still retaining control over the tangible held.

The reported physical explorations with the objects and their relations (e.g., piling or tossing objects) seem to be a vehicle to discover the digital domain of a tabletop TUI: a dialogue between physical explorations and real-time feedback supports discovering hidden connections between the physical and the digital domains. As envisioned by Ishii et al. [2012], we are still in the infancy of TUIs, and changes in material and physical properties are far from being represented in the digital domain. For example, the Reactable only registers two dimensions, and so piling objects has no effect on the interface.

A number of challenges arise from these physical explorations. First, the Reactable's tangibles operate as controllers where the output is projected on them as visual feedback, but the tangibles lack embedded information, as it is the case of Siftables [Merrill et al. 2007]. An open question is to what extent having computationally embedded tangibles instead would influence this trial and error dialogue between the digital and the physical domains. Second, an assumption in the

Reactable is the number of parameters that can be manipulated (from one to three in this Reactable version), and the number of inputs and outputs (where the outputs are limited to one or none depending on the object of this Reactable version). Yet, in the unit generator paradigm, a unit generator includes multiple parameters and inputs/outputs. A finer-grained representation of the unit generator paradigm on a TUI is a challenge: we are still in its infancy stage.

### 9.3 Tabletop Musical Improvisation

Awareness issues of who is doing what can appear in tabletop interaction when there is lack of control of the interface, mainly during early sessions: Examples such as the preview technique show how a major control over time is developed including awareness of individual actions. Blaine and Fels [2003] propose to provide multimodal inputs and outputs in collaborative interfaces as a reinforcement of individual actions. Zuckerman et al. [2005] suggest using multimodal representations with TUIs to engage different senses (e.g., touch, vision, auditory) and support different learning styles. Both approaches are based on the identification of actions through a sense-based perception. Thus, it seems that a possible solution to cope with awareness issues in early sessions is by providing multimodal feedback, which appears to support different individual and group dynamics.

A tabletop interface, the free-form nature of the activity and the characteristics of the Reactable's interface seem to promote egalitarian participation with dynamic role changes (in contrast with more hierarchical structures). This exemplifies an *interconnected musical network*, a term coined by Weinberg [2005] to describe interdependent and dynamic networks that promote social interaction. Musical improvisation with the Reactable contrasts with improvisation in traditional ensembles such as jazz combos: musicians play individual instruments in the latter, whereas musicians share the same interface in the former – a fact that provides new perspectives and roles to the practice of improvisation. Thus, while in jazz ensembles musical improvisation tends to be a self-reflective process [Sawyer 2003], the Reactable provides opportunities for musical knowledge to be transmitted in a collective reflective process through a shared interface with real-time visual feedback. Our data showed how musical tabletop design promoted equal participation, and dynamic and versatile roles, in agreement with Hornecker et al. [2008]. This contrasts with the idea of a need to define roles in collaborative music, when sharing the same digital media [Brown 2006]. A number of dialogues were reminiscent of traditional musical ensembles, in particular jazz ensembles, where there is a distinction between rhythmic accompaniment and melodic soloist roles [Monson 1996]. However, variations in tempo were easily executed with the Reactable (e.g., the metronome object controls the global tempo), and changes of voices and musical roles tended to be fast-paced, features that seem to be particular to this musical tabletop interface. In agreement with Day [2010], the endings of these sessions appeared to fulfil the role of resolution and wrap-up as it happens in jazz musical improvisation (and, by extension, other musical genres as well). Yet we observed equal participation, which is different to traditional endings of jazz solos.

Nonparticipation is traditionally associated with a passive attitude, whereas here it can be an active role (e.g., a set of tangibles left on the surface can keep behaving with no human intervention). Nonparticipation may have happened for several different reasons: first, the available limited number of resources, the size and shape of the tabletop surface, and the number of collaborators appear to determine quite considerably the performance; second, with the Reactable it is not necessary to

physically play all the time in order to produce sound; and, third, silence can be also considered a contribution in music performance [Cage 1961]. Thus, nonparticipation can be considered a positive aspect in tabletop musical improvisation.

The capacity of expressing varied and creative narratives with different levels of complexity by all group members seems to play a key role in improvisational activities on tabletop TUIs and group development. These narratives include an improvised sequence of events with a beginning, development, and ending. The non-linear nature of the system makes each session different and difficult to reproduce. The following elements appear relevant to supporting these collective narratives: sequenced actions (e.g., dialogues between users such as call-response, adding or removing objects sequentially, incremental increase or decrease of objects' parameters); individual and shared structures (e.g., individual vs. shared threads); GLs (e.g., global volume or global tempo) apart from local control of structures; serendipity actions (e.g., dynamic patching); synchronicity of actions (e.g., all threads in synch); customisation of data (e.g., loading your own data on cube objects); or modularity (e.g., basic vs. complex structures).

#### 9.4 Situated Peer Learning

Verbal and nonverbal communication were used for collaborative peer learning during musical improvisation on the Reactable. Groups developed ensemble skills such as solving problems in team, sharing limited resources, or social tinkering. This agrees with Harris et al. [2009] and Rick et al. [2011] who present interactive tabletops as a suitable environment for learning in collaboration. The evidence of wide use of mimicking is comprehensible, being a common practice typically found between musicians, even more so in improvisation. As Bailey [1993] suggests, improvisation is based on imitation, repetition and exploration. Mimicking is greatly facilitated by tabletop TUIs in general, and the Reactable in particular, because participants are co-located and face-to-face with the same interface, with no disparity in the tangible objects available to them. Thus, interactive tabletops permit straightforward visibility of collaborators' bodily actions over the tabletop surface, which can be seen and imitated immediately. This approach permits reproducibility of constructions with object categories (e.g., SGs or FXs) including repeated or unique tangible building blocks (e.g., different SGs or repeated CTs), or gestures. Yet with the Reactable, this reproducibility is based on a concrete representation of building blocks: a modular synthesizer. Little research exists on digital building block systems that can represent instead a range of abstract concepts, which can change their meaning although using the same collection of building blocks, for example, Zuckerman et al. [2005]'s MiMs. Tabletop TUIs seem to offer an opportunity to explore MiMs including multiplicity of meaning and customisation of tangibles, a promising area of research.

We found differences between groups in terms of how the same problem was solved using verbal communication, and we identified similar or different techniques being mimicked, depending on the groups. Both explicit and implicit peer learning appear to be used in a practical context of learning by doing. The learning process seems to be similar to situated learning, where knowledge is shared and co-constructed within a context and *community of practice* (CoP), understood as a group that shares an activity [Lave and Wenger 1991]. Yet the literature has typically focused on examples of beginners learning from experts. Our participants learned from each other (groups were based on similar level of musical expertise), and, only in the case of G3, a newcomer was instructed in later sessions on certain techniques.

As with other TUIs in education, *situated peer learning* happens through hands-on, social tinkering [Zuckerman et al. 2005]. Our findings show how group dynamics and tabletop design can influence situated peer learning. The peer learning happens, in agreement with Suchman's [1987] findings, in a situated social and technological context: a particular social context, which varies depending on the group dynamics; and a particular technological context, here the Reactable, which raises new challenges to group collaboration and arguably encourages each group to cultivate a new CoP by doing and learning from each other [Lave and Wenger 1991]. Our findings also agree with Rick et al. [2011] who discuss the benefits of supporting group dynamics on interactive tabletops. Furthermore, theoretical accounts of collaborative learning by doing, such as Roschelle's [1992] notion of *convergent conceptual change* are relevant here. In such learning, people gradually construct a shared, convergent meaning, which is situated [Suchman 1987] – the construction of shared meanings depending on the actors and the technology used.

### 9.5 Design Considerations for Tabletop Collaborative Learning

We derive the following set of design considerations from the previous discussion on the topics that emerged from data analysis at interface, interaction, musical, and social group levels: Reactable interface (1–2), tangible interaction (3–5), tabletop musical improvisation (6–7), and situated peer learning (8–9). These design considerations aim at supporting collaborative learning on tabletop TUIs using constructive building blocks for hands-on creative activities:

- (1) *Allow self-regulation of space.* A tabletop TUI with territorial constraints (e.g., individual vs. shared spaces) seems that can be harmful for a free-form activity such as improvisation. The lack of territories seems to promote a self-regulation of space, which can be beneficial for musical improvisation. The nature of this self-regulation appears influenced by the available space, the number of group members, the available number of tangibles and their relations (e.g., from local to global), and the progressive control of the interface.
- (2) *Provide automated connection mechanisms.* Creativity can be computationally enhanced with automated system behaviours, yet we should rethink how to complement them with an optional mechanism to control them. An interactive tabletop with a mechanism that automatically connects the tangibles' inputs and outputs (e.g., Reactable's dynamic patching) seems to be useful to promote serendipitous actions and creative discovery. Yet it can also be a constraint when users need more control over connections. In this case, an additional mechanism to manually control them could be considered.
- (3) *Allow modularity and scalability with objects.* A modular tangible interface seems to allow for simplicity and combinatorial complexity, which results in multiple compositional possibilities. Yet a future challenge is the scalability of a modular set of tangibles on a tabletop interface beyond the physical domain with no detriment of learning through construction processes.
- (4) *Provide synchronicity in actions with objects.* A tabletop tangible interface with synchronicity mechanisms (e.g., global tempo clock, real-time feedback) seems to promote bodily coordinated actions between users when interacting with the tangible objects. The nature of these embodied gestures fits well with instrumental interaction in collaborative learning, hands-on activities. These gestures require sufficient space to be performed.

- (5) *Allow real-world interactions with objects.* We are still in the infancy of mappings between the physical and the digital domains in TUIs with much to explore from real-world interactions. The digital domain in tabletop TUIs, which is usually represented by real-time feedback, seems to be discovered by a trial and error exploration of the physical properties of the tangibles and their relations (e.g., piling or tossing objects), and it becomes easy to be reproduced by others. The actions performed in this independent physical exploration from the digital domain may inform future directions of tabletop design as connectivity between both domains, and go beyond 2D mappings as it happens with the Reactable.
- (6) *Allow real-time multimodal feedback and new approaches to participation.* Transferring traditional creative group activities such as improvisation on interactive tabletops presents new challenges to group collaboration (e.g., awareness issues, participation roles). Providing multimodal feedback can mitigate awareness issues and facilitate different learning styles. Permitting flexibility in roles and participation (e.g., active nonparticipation, egalitarian participation) with no disruptions on the activity seems relevant here (in contrast with more fixed and hierarchical roles in traditional improvisation).
- (7) *Provide modularity and flexibility for musical development.* A flexible and modular tabletop TUI seems to promote a variety of combinations of musical expression and control based on object manipulation. This can benefit different group musical development in long-term, creative, narrative-based activities.
- (8) *Allow reproducibility and multiplicity of meanings.* Reproducibility of structures and behaviours (that is, copying of structures or imitating gestures) facilitates social tinkering, and learning by doing. The Reactable's approach to constructive building blocks is constrained to a concrete representation: a modular synthesizer. A range of abstract representations using the same collection of building blocks would allow modelling other systems, which could be beneficial to long-term learning in other contexts.
- (9) *Allow for a variety of styles and situations.* A modular and flexible environment based on constructive building blocks seems to be suitable with group dynamics and situated peer learning. This approach promotes different group development processes, social tinkering, and learning styles. It includes no interface divisions to the number of users and their positions, who can join or leave the activity at any time; supporting different problem solving styles; or supporting different levels of composition complexity.

## 9.6 Study Implications

The implications of our study are threefold:

- (i) *For design* – our research suggests future directions in tabletop design for interfaces of construction processes. As just discussed above, constructive building blocks seem to favor collaborative learning, which can be useful for constructivism approaches to learning with technology.
- (ii) *For research* – a longitudinal study based on an unstructured, narrative-based activity such as improvisation can be a useful vehicle for exploring novel interfaces and changes over time through collective practice, which is relevant in HCI. This methodological approach can provide a finer level of granularity of skill development, conceptual development, and group development. Existing time issues in research for developing and evaluating novel prototypes, as it happens with tabletop TUIs, can be coped with either strengthening connections with

industry, or with building more general-purpose development frameworks to avoid reinventing the wheel each time.

- (iii) *For education* – constructive building blocks on a tabletop tangible interface may be a useful vehicle to cope with multidisciplinary learning activities. For example, a tabletop TUI can support a classroom where the teacher can guide students to construction processes of learning based on situated experiences, which can course them to unique conclusions using a computer enhanced environment. A tabletop TUI promotes gesture-driven interaction, which is so important in hands-on approaches to learning, and at these ages.

### 9.7 Study Limitations and Future Work

We attempted to make up for the lack of ecological validity of a lab study, if compared to a real-world scenario, by: (i) using a casual and relaxed setup; (ii) working with expert musicians, who are familiar with musical improvisation and are used to play (and engage) for long time in group work, even with strangers; and (iii) studying musical improvisation, a free-form activity that includes protocols (e.g., beginnings, endings, dialogues) that precisely cope with playing in group with strangers and not being stuck. Moreover, a similar in-the-wild study would be difficult to conduct: it is unlikely to find several music bands having the same musical tabletop instrument in their music studios. Furthermore, with growing expertise, learning and development processes slow down and become hard to observe. We would need to observe groups at increasingly longer intervals. Here, we have therefore focused on the initial phase of learning to jam together on the Reactable.

Another limitation could be seen in studying only four groups. We have therefore focused on a detailed qualitative analysis. Yet we believe that the developments we have observed are typical of the user group (i.e., expert musicians) chosen for the study, with a range of behavioural patterns having been consistent across these four groups. At the same time differences in group dynamics observed with just four groups indicate the variety to be expected if more groups were to be studied.

For future work, we identified several topics. Future research could concentrate on to what extent collaborative learning differs in other contexts (e.g., non-musicians or children). This could include conducting research in ecologically valid settings (e.g., schools or museums). Other topics could be further studied in more controlled settings. For instance, it could be investigated how to better support individual and group awareness with different modalities of real-time feedback (e.g., auditory, visual, haptic), which could be useful for general-purpose interactive tabletops using sound. It was out of the scope of this article to consider quality and progress of the music style of the groups, or including thick descriptions of musicians' gestures: future studies on these topics could inform research on musical tabletops and nonverbal communication studies.

## 10. CONCLUSIONS

In this article, we investigated collaborative learning and group development of expertise during musical improvisation on the Reactable. We examined challenges and opportunities of using a set of constructive building blocks on a tabletop tangible interface over time. We observed the interface, interaction, musical and social levels. Our findings suggest that, similar to other TUIs based on constructive building blocks, it promotes hands-on, social tinkering and development of modular structures from basic to complex. Furthermore, tabletop interaction especially promotes group coordination and learning by mimicking others through instrumental interaction in a

situated context. It also raises new challenges to group collaboration concerning awareness issues or participation roles. We also found that the Reactable's lack of territorial constraints and its automated connection mechanism promotes exploration and creative discovery, which is useful to positively motivate collaborative learning in creative group activities. In sum, our research suggests that this approach can promote collaborative and peer learning, which can inform constructivism approaches to learning using a computationally enhanced tabletop environment.

We hope our study will promote future design, research, and education approaches to collaborative learning on tabletop TUIs, and it will also inform future research on nonverbal communication studies.

## ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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