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 describe 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 reveal 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 support learning by doing and peer learning, which can inform constructivist 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

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traditional and interactive tabletop collaboration, which has been used to inform the 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; Pontual Falcão and Price 2011; 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], Speeelpenning 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 specific tabletop interfaces over longer periods of 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 quite simple, and thus research has arguably focused on the 'low floor'—the ease of immediate use of generic tabletop interactions—instead of the 'high ceiling' of expert performance with a dedicated tool. While simple is appropriate for tabletop systems for public spaces (e.g., Hornecker, [2008]; Marshall et al. [2011]) in order to make progress in tabletop research, we argue that it is necessary to move beyond studies of simple demonstrator applications. Instead, as with previous generations of interactive systems, we need to detail how people use tabletops for a variety of real purposes in order to better understand the strengths and limitations of this novel platform. Back in the 1990s, for example, Grudin [1994] suggested that for designing technologies for office group work, research should be done in the workplace in order to understand real problems.

In this article we describe findings from video analysis of four groups improvising using 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 connected together. The analysis focused on overarching research questions on the challenges and opportunities for groups in using a tabletop TUI over time. The focus was an interaction analysis of how expertise developed in specific episodes over multiple sessions with the Reactable, rather than summaries of the immediate understanding (or lack of it) of novice users with a simple or generic system. In particular, we investigated:

— *Interface characteristics*: how the Reactable's interface characteristics influenced group behaviour over time, in particular its lack of territorial constraints
— *Tangible interaction*: how the properties of the tangible interface facilitated group progress and the development of expertise; the nature of gestures in group tabletop interaction and learning; and the usage of tangible objects
— *Musical improvisation*: how tabletop musical improvisation brought new challenges compared to traditional ensembles; and how the organisation of improvisation developed over time
— *Social factors in the development of expertise*: the nature of collaborative learning through constructive processes on the tabletop TUI; and how this supported 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 multi-session 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 detail how the Reactable's interface promotes group coordination and learning through instrumental interaction in a situated context, supported via the system offering a shared space and real-time feedback. It also creates challenges for group collaboration such as maintaining awareness or understanding participation roles. We found that the Reactable's lack of territorial constraints and its automated connection mechanism (*dynamic patching*) were suitable mechanisms for creative group activities because they promoted exploration and serendipitous creative discovery, which could motivate collaborative learning. We furthermore found some differences in musical coordination patterns compared to traditional improvisation practices (e.g. in jazz), such as dynamic and fast-paced role switches and equal participation of members in endings. Our findings are discussed in terms of design considerations for designers, developers, manufacturers, educators, researchers and practitioners. We conclude that the Reactable's interface of interactive tabletop coupled with constructive building blocks promotes learning by doing as well as peer learning. These findings inform constructivist approaches to learning on computationally enhanced tabletops.

This study constitutes the first detailed examination of collaborative learning over multiple sessions with a tabletop system. 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. All of these types of systems (i.e., interaction only via touch, only through object manipulation 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 tabletops (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] observed 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. Pontual Falcão and Price [2011] noticed that interferences between users during a scientific task can sometimes promote group discussion towards a joint solution and inquiry learning. 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. They 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]; Pontual Falcão and Price 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, in this paper we 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 nonverbal communication: in particular, *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 processes in music performance [Kawase 2009; Keller 2008; McCaleb 2011], on the collaborative experience in music [Blaine and Fels 2003], or on shareable and multi-user musical interfaces [Jordà 2005], little research has investigated the communication processes and the transmission mechanisms between participants in the field of musical improvisation using tabletop technology. This is an aspect of essential interest for our study. An exception are long-term studies of musical improvisation and communication in traditional contexts, 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 [2013] studied the distributed use of visual shared representations; and Pugliese et al. [2012] investigated situated interaction and collaboration during mobile group improvisation. Swift [2012] carried out instead 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 laptop ensemble over the course of 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 a new direction in tabletop studies.

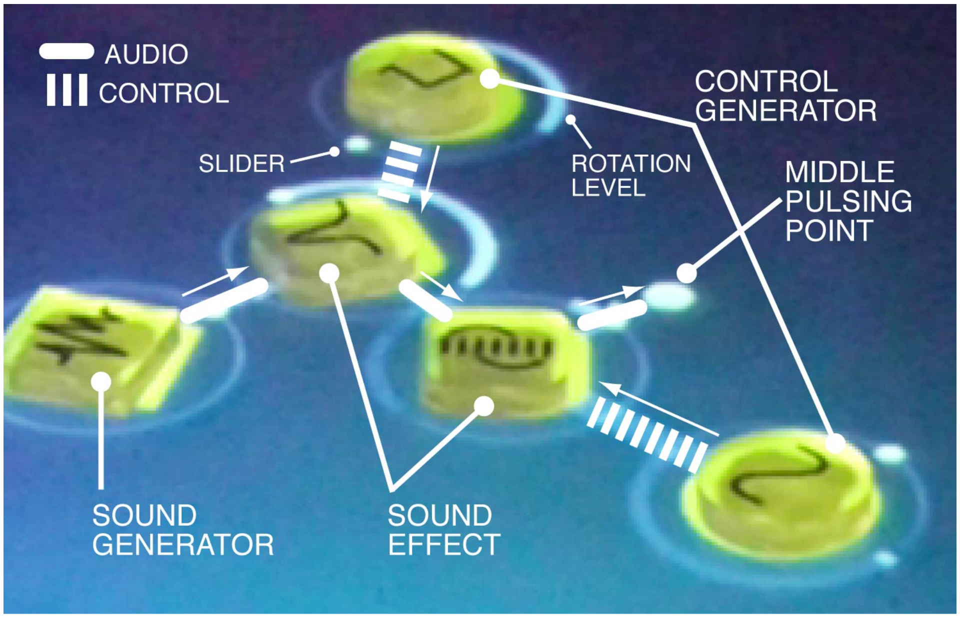


Fig. 1. A Reactable's thread.

3. STUDY

In this section we present a detailed account of and motivation for the study design.

3.1 The Reactable

The Reactable is a commercial real-time modular synthesizer [Jordà 2008], which is used 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[1] with a 100cm diameter including a rim area of 10cm), and it combines multi-touch with tangible object manipulation as input. The Reactable's TUI enables the construction of a variety of configurations of building blocks to produce sound. A set of physical objects allows users to create music by building *audio threads* (see Figure 1), each thread representing an audio channel (i.e., a sound source that can be operated individually). Here, we use the term *thread* to refer to the physical connection between objects whilst *voice* refers to the character of the musical sound resulting from this connection (e.g. melodic voice). These objects have different functions, each represented by different shapes: *sound generators* (squares and cubes) to create sounds, *sound effects* (rounded squares) to transform sounds, *control generators* (circles) to control other objects and *global controls* (polygons) to control global parameters. A player's own sound files or samples can also be loaded and associated with the different sides of a cube, which will be played in a loop.

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 by sharing the same global tempo. Each thread is shown in a different colour from a defined palette, and is built from interconnected objects. The sum of the audio threads constitutes a *patch*. A thread needs at minimum a

[1] See: http://reactable.com/products/experience.

sound generator in order to generate sound[2,3]. 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 carried out 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 via the rotation angle, the finger on the projected slider on the right side of the object (see Figure 1), or the distance to the next object in the thread (alternatively the distance to the centre in case of the last object in the thread).

In addition to the influence from analogue and digital modular synthesizers such as Robert Moog's or Donald Buchla's Voltage-controlled synthesizers [Moog 1965], the sound synthesis and control method implemented in the Reactable interface can be seen as a physical representation of the unit generator paradigm invented by Max Mathews [Roads 1996, p. 89–90], 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 [Roads 1996, p. 787–788]. In the Reactable, each object has a number of inputs (from none to multiple) and outputs (one or none) depending on its category, which make the connections between objects possible; connections can be either control signals (i.e. when the destination is a parameter of a unit generator) or audio signals (i.e. when the destination is either an audio input of a unit generator or the global audio output).

Unlike visual programming musical languages (e.g., PD or Max/MSP cf. Puckette [2002]), the Reactable supports real time *dynamic patching* [Kaltenbrunner et al. 2004], permitting 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.

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

Some projects such as Sony's Block Jam [Newton-Dunn et al. 2003], or a 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

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

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

operated by the tangibles but the output is displayed on a separate screen. Siftables are a multi-purpose platform, which includes a music sequencer [4], 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 and improvisation 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 with 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 understanding and group coordination in musical improvisation, we chose to study participants who are not already accomplished Reactable performers.

Our study investigated four groups of co-located musicians collaborating around the Reactable: each of these played with the Reactable over a series of four sessions, which were scheduled in close succession over the course of one week. Given that 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 setting, allowing for control of the collected video data used for further analysis.

Our approach follows other studies (cf. Hornecker et al. [2008]), beginning with Suchman's study of photocopier use [Suchman 1987; cf. Rooksby 2013], in conducting a naturalistic observation of activity within a lab setting. We attempted to create a casual setup, resembling the settings of 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 from the busy classroom areas and 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 in rehearsal and performance settings. Thus, setting and activity type were designed to be familiar for our participants.

[4] See: http://www.ted.com/talks/david_merrill_demos_siftables_the_smart_blocks.html.

Fig. 2. Participants jamming the Reactable.

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, with 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 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

Sessions were said to last for 15–45 minutes. 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 which were initially distributed around the rim of the table: 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 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 and encouraging 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 point (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 activities, particularly where object-manipulation is a central part of the activity. We identified a number of themes: some 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. 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 used Elan[5] to analyse the videos.

Representative video extracts were repeatedly viewed and discussed by three of the authors. We focused on verbal communication and nonverbal communication themes, of which those related to nonverbal communication were divided into musical, physical and interface-related (see Appendix A). We also focused on lower level categories specific to the Reactable interface such as territories and thread ownership (see Appendix B). Links to the video extracts analysed in this paper are listed in Appendix C.

4. GENERAL SESSIONS OVERVIEW

We first give an overview of the sessions and the general group and musicians' behaviours. The sessions tended to last from 35 to 45 minutes (but sometimes longer):

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

All groups used the full time available for their sessions until the room had to be freed. Groups used cubes differently: G_1 and G_b only worked with preloaded samples, whereas 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) also loaded their own sounds.

An environment resembling a rehearsal music room setting was successfully created. Participants demonstrated 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. Groups concentrated on the task despite the extra furniture of the room, which seemed to go unnoticed.

Group dynamics tended to be as diverse as in a real rehearsal: in the beginner group G_b, one participant arrived five minutes after the scheduled time twice, and thus the other group member of the duo group 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 generally a 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, which is detailed in Section 5.1.1); 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 here.

5. FINDINGS: INTERFACE INTERACTION

In this section we focus on the most prominent of the Reactable's system design characteristics. The shared table space does not automatically provide individual territories for each player. It can be viewed as providing shared control of a single musical instrument as well as requiring 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. Our findings indicate that these two interface characteristics promoted exploration and serendipitous discovery in a collaborative learning situation, where participants acquired mechanisms to self-regulate the shared use of space, and developed new ways of sharing threads in the pursuit of musical effects.

5.1 Territoriality

Given it is unusual to be able to share an instrument [Jordà 2005], our interest was to find out how participants dealt with this and what kind of territorial behaviors might emerge. Scott and Carpendale [2010] and Scott et al. [2004] 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 (on the Reactable the global tempo pulsing point and sound output constitute the centre). We assume that the distribution of personal and shared areas depends on the number of users and the shape of the tabletop surface (see Figure 3). While territories assume a spatial distribution of ownership, we had to consider in addition that thread ownership is object-based and may change dynamically as threads change, regardless of the position of the individuals.

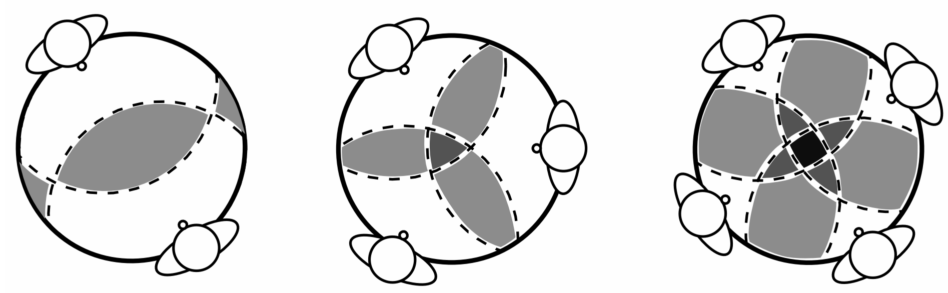


Fig. 3. Imaginary divisions of personal and shared areas.

We observed and analysed a number of territory-related behaviours:

— *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 takes* (taken from the surface table area) or *passive takes* (taken from the rim area close to another person, who is not currently using it).

— *Gives*: Handing an object to somebody else for individual use, which can be *active gives* (given on the surface table area) or *passive gives* (given onto the 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.

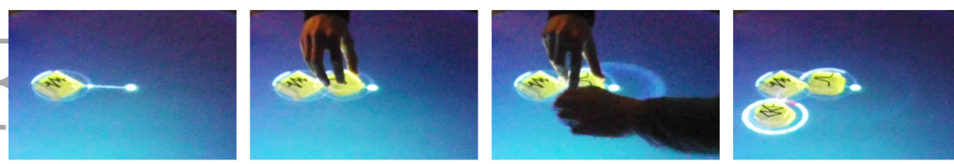


Fig. 4. A shared thread.

5.1.1. Individual territories, takes and gives. Musicians tended to play within the area nearest to them, confirming a tendency for the establishment of personal areas. The larger the 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 happened with group 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 session S_1 by G_b, where M_1 invaded a number of M_2's threads, sharing them or taking them over completely (i.e.; they became his 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 the situations where 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 the vignette in Figure 5 (see video 1A). This occurred near the middle of S_3 by G_b; the surface table area was divided into M_1 and M_2's individual spaces. Suddenly, with no verbal exchange, M_2 (musician on the left in frame 1) left the room to attend to an urgent phone call, leaving his threads playing. Then, M_1 (musician on the right in frame 1) interacted with all the threads on the table, fading the volume out of all of M_2's threads (frame 2), even moving to where M_2 was standing (frames 3–4). Then M_1 moved back to his original position, and started two new threads with two cube objects, one of which incorporated an FX from a M_2's thread by dynamic patching, and thus his thread occupied part of M_2's space. After approximately two minutes, M_2 came back to the room, went to his initial tabletop position and asked "How is mine going?"; M_1 replied: "I've faded it out"; and M_2 agreed, saying "Okay". Then M_1 moved the cube towards himself making the connection with M_2's FX disappear. This example shows how individual spaces and threads are dynamically reconfigured depending on the number of musicians in the room.

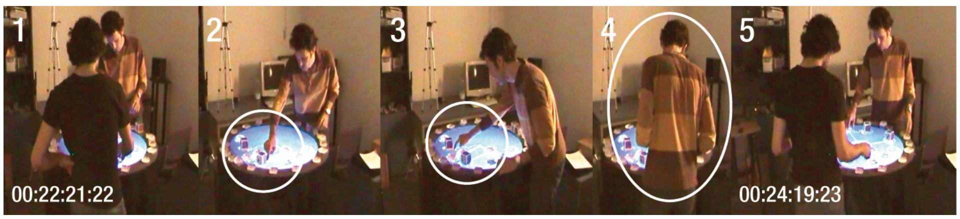


Fig. 5. Dynamic reconfiguration of individual territory.

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 of becoming familiar with the objects, after an initial period of 15–20 minutes of improvisation. Those musicians who loaded a cube object 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 performed passive takes, 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.

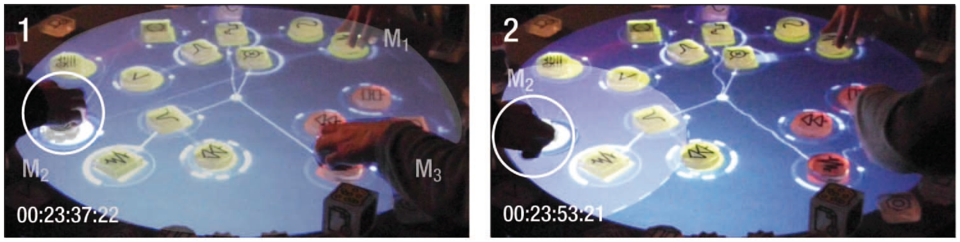
How passive takes evolved indicates that the objects and their categories became better known over time. In early sessions, objects taken generally belonged only to one or two categories: sound generators (G_3), sound effects (G_1), sound generators and sound effects (G_2) or sound generators and global controls (G_b). During the last sessions, objects from all categories were chosen, except for G_1 who did not take global controls. This indicates 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, with 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, which are fully explained in Section 6.2 (see Figure 8), 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.

This data reveals that individual spaces are negotiated flexibly with no need for system level constraints, and that control of the objects collection improves over time.

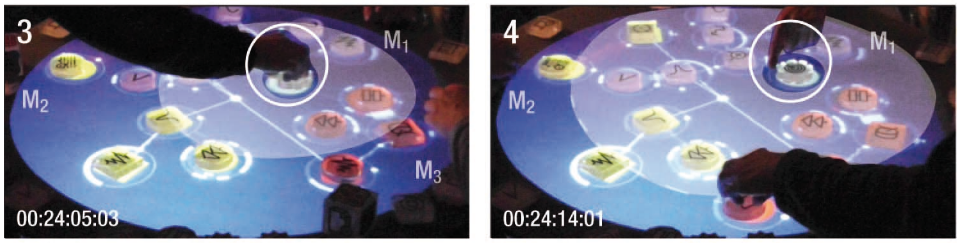
5.1.2. Thread ownership and shared threads. Threads tended to be shared by the entire group when they occurred in the spaces in-between musicians or in the middle of the table (for example, see Figure 11, bottom, which is fully discussed in Section 7.2). This indicates the association of the centre and in-between spaces as shared areas. Shared threads were created either intentionally or unintentionally: during early sessions, unintentionally shared threads that were triggered by dynamic patching were rather common (see Section 5.2), whereas in the later sessions participants had 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 nature of invasions and of changes in thread ownership modified in character over time towards using them for a musical intention: 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 for 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 6 (see video 2A), which illustrates a sophisticated invasion of others' threads that was not just related 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 an effect is not related to physical proximity, raising the question of when an invasion creates a shared thread because the interferences are continuous instead of discrete. Another example is shown in Figure 14, which is fully discussed in Section 8.2, 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.



In S_4, M_2G_1 puts the radar trigger object next to his personal space. The range of the tempo set with the object covers the whole tabletop surface affecting all the threads.

M_2G_1 rotates the object and thus changes the speed of the radar. He also moves the slider and limits the range to the area next to himself.



M_2G_1 drags the object to the opposite side of the table. The range of the radar trigger is now affecting the personal spaces of M_1G_1 & M_3G_1.

M_1G_1 takes now control over the radar trigger, and expands the range to include M_2G_1.

Fig. 6. 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.

This data shows that apart from individual spaces, there are shared spaces, which seem to be negotiated flexibly with no need for system level constraints. In early sessions, shared threads are a result of exploring the Reactable interface, whilst in later sessions there is a clearer musical purpose. It is notable that we only found very few instances where invasions or sharing of threads was objected to – they tended to be integrated ad-hoc into the musical development and thus became part of an accepted repertoire of musical actions.

5.2 Dynamic Patching

We found several examples of participants triggering unintentional effects due to the Reactable's dynamic patching mechanism. Unintentional interference with other people's threads, or even the entire patch, was not uncommon, especially during early sessions. Sometimes it was difficult to discern the functionality of an object (see Section 7.1 and Section 8.2). If any of these events occurred, the musicians either treated it as a serendipitous event, integrating it into their ongoing improvisation and building on it, or attempted to repair and revoke it. An example of an unintentional effect of dragging an object in an early session (G_1S_1) is shown in Figure 7 (see video 3A) where M_3 (musician on the right) has an individual thread of two objects: a slicer effect (FX) and an 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 threads belonging to M_1 (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). By contrast, Figure 11 (bottom), which is discussed in

Section 7.2, provides an example of the intentional use of dynamic patching and serendipity actions at the ending of a session.

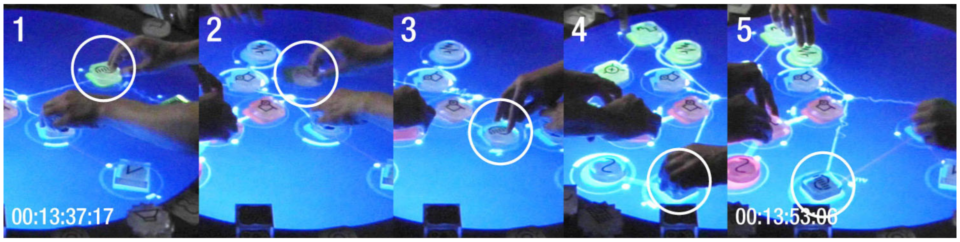


Fig. 7. Triggering unintentional effects with dynamic patching.

These examples reveal that dynamic patching of automatic connections is a useful mechanism for promoting hands-on exploration and discovery of the interface in early sessions.

6. FINDINGS: TANGIBLE INTERACTION

In this section we present findings that focus on more generic aspects of physical and tangible interaction, whereas the previous section focused on features that were more specific to the Reactable interface. In particular, we describe how aspects of the control of tangibles developed over time; on gestural aspects of the interaction, such as their performative and communicative value; and of physical explorations; and relate them to properties of the tabletop tangible interface. It is notable the lack of overt eye contact and explicit communication despite of high levels of awareness evidenced in the collaborative activity.

6.1 Development of Control

All groups evolved towards utilising more sophisticated structures and techniques over the four sessions. Groups developed structures from initially not replicating objects with similar functions in the same thread to replicating them in later sessions with the effect of yielding more complex sounds (e.g., from using single sound effects to using a number of sound effects at the end of the thread); and from basic sequential threads of objects connected one after the other to more complex structures. Also, groups progressed from using individual techniques, such as dragging, swapping or twisting objects, to combining two of these techniques simultaneously.

Usually threads started with a sound generator (SG) followed by or simultaneously used with other objects. Yet groups 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), which also is discussed in Section 7.2, illustrates a preview technique used by M_1 in S_2 using two filters, after using this technique with one filter in S_1 (see video 7B):

> 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).

The modular approach of the Reactable's tangible interface allows musicians to build a variety of compositions over the four sessions, from basic to very complex. Furthermore, some musicians develop techniques over time that show how potential awareness issues of individual actions can be controlled over time.

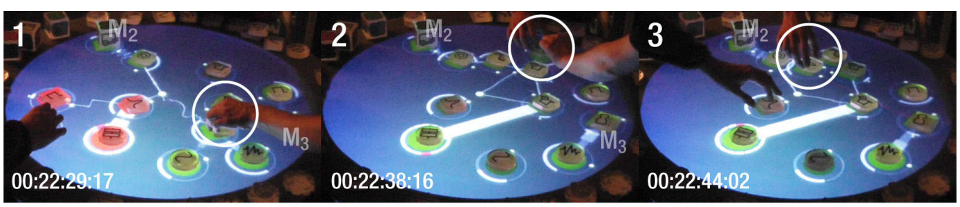
6.2 Gestures

In a study of clarinettists' movements, Wanderley and Vines [2006] used the term *ancillary gestures* for those gestures that without being strictly necessary support the sound-producing gestures. Jensenius et al. [2010] developed this typology of gestures including i) *sound producing gestures*; ii) *ancillary gestures*, which support sound-producing gestures; iii) *communicative gestures* for communication between performers and the audience, including eye contact; and iv) *sound accompanying gestures*, which are engaged body gestures not directly related to sound production. We here focus on movements made by group members that are relevant to tangible and social interaction. We base the following analysis on Jensenius et al.'s typology (a detailed investigation of musicians' gestures is beyond the scope of this article).

— *Sound producing gestures*: In our study, sound producing gestures are connected to instrumental interaction, constituting "activities that crucially involve the manipulation of physical objects" [Jordan and Henderson 1995, p. 65]. We identified instrumental interactions for sound production, including both non-exaggerated and exaggerated movements, 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, i.e. movements beyond that necessary to interact with the instrument. Yet, there were also occasions of exaggerated movements, for instance when performing certain techniques such as *strobing*, involving 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 movement, lifting the tangible object high above the surface while moving their upper body in synchrony, emphasising the rhythm. These movements seemed to add bodily emphasis on specific actions, which could also be noticed more easily by the other individuals.

— *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 all sessions, there were no collisions of arms or hands when musicians took objects from the areas of the rim nearest other participants, despite a general lack of verbal communication. An example is a handover shown in Figure 8 (see video 4A): 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]). This seemed to be facilitated by the shared visibility of the workspace, which in turn was supported by real-time audiovisual feedback on instrumental actions on the table. Explicit eye contact during verbal exchanges was mostly observed during beginnings or endings and occasionally in-between sessions (see Section 8). 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, including shaking hands in G_1S_1 or clapping hands in G_2S_1.

— *Sound accompanying gestures*: Some groups utilized more sound accompanying gestures than others. Although the extent of this varied between groups, the occurrences indicate a connection between gestural interaction and group dynamics. These gestures were generally full-body movements. In G_1, participants remained motionless with only occasional shifts of the 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. Figure 9 shows an example of bobbing (see video 5A), where M_3 (left) is bobbing his head rhythmically up and down in S_1 (frames 1–3), and so does M_1 (right), also bobbing his head (frames 3–4). *Bobbing* may support the individual 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 time with the music. In G_b, participants remained motionless with occasional shifts of the upper body towards the table surface for object manipulation and also some swaying from side to side. In contrast with traditional ensembles, there were few overt gestures to help synchronise the group: a synched, shared interface that everyone can easily view 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. 8. Handover.

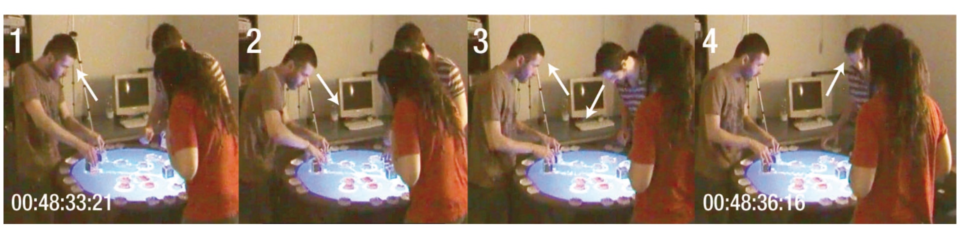


Fig. 9. Bobbing heads.

Overall, a range of bodily actions and hand gestures are performed with the Reactable with little direct eye contact and while focusing attention on the tabletop surface: exaggerated and non-exaggerated sound producing gestures (e.g., manipulations including gestures such as strobing), ancillary and communicative gestures (e.g., bodily coordinated actions such as handovers), and sound accompanying gestures (e.g., bobbing and nodding heads). The use of tangible objects on a shared interface with synchronicity of actions and real-time feedback seems to promote all these types of bodily interaction that lack eye contact but are coordinated with the sound produced.

6.3 Explorations

We further noticed several situations where groups explored the limits of the tangible tabletop interface, such as adding all the available objects to the surface (G_3 in S_2–S_4), stacking objects (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 on one 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), which is also explained in Section 7.2.
An approach of trial and error exploration with the physical tangibles seems to help discovering the digital domain in TUIs, which can in turn be seen and imitated by others.

7. FINDINGS: MUSICAL INTERACTION

In this section, we detail the findings of both individual and group interaction in tabletop musical improvisation over time. We here focus on the musical elements employed by the groups over the course of the four sessions and on how the coordination and organization of the improvisation activity developed over time. It is out of the scope of this article to consider the music style of the groups, including its progress, and the quality of the improvised music. If we compare tabletop musical interaction with traditional improvisation, there are notable differences such as the presence of more fluid and quick changes of musical roles. These are, as we argue, an effect of the shared interface, which enables new forms of musical collaboration.

7.1 Individual Interaction

Video data revealed that issues with understanding the interface functionality mainly arose in the initial sessions, where musicians had difficulties with particular features of the interface, for example, misusing the programmer object designed for reprogramming the objects with samples. 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 indication (e.g., G_1 and G_2). Despite occasional difficulties, groups 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 7.2 and previously in Section 6.1.

We observed a number of solos (i.e., leading voices) in all four groups, which increased in sophistication over time, although some groups were more inclined to perform solos (esp. G_3 and G_b) than others. Some solos were built up to an existing accompaniment (i.e., a leading voice vs. accompaniment voices) and some triggered dialogues (as detailed in the next section). There were individual musical explorations: a subset of these were mimicked and further developed by other peers as described in Section 8.1; others were developed individually, such as creating serendipitous 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_3G_1 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., in G_1 it happened with musicians M_1 in S_4, and M_2 in S_2–S_4; or in G_3 it happened with musicians M_2 in S_1–S_4, M_3 in S_1–S_4, and M_4 in S_4).

Individual actions related to awareness issues seem to happen more often during early sessions, and interface feedback seems to help users in the identification and control of their own actions. Moreover, musicians developed different and dynamic individual voices, including nonparticipation (i.e., standing back) in a positive sense, leaving their patches 'alive' and playing.

7.2 Group Interaction

We found egalitarian participation and no evidence of fixed musical roles. The configuration of the objects and thus the resulting 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 based on a relatively fixed rhythm section and a variable soloist section, with a dynamic tension between the two [Monson 1996, p. 82–83]. We identified a number of dialogues between musicians. Our analysis looked at the nature of these dialogues based on dichotomies such as homophonic (i.e., a single voice plays a melody) vs. heterophonic (i.e., multiple voices playing a melody with variations), and elements of musical forms such as call-response or rhythm vs. melody (cf. Pressing [1984, 1988]). Over the four sessions, these dialogues became more complex and sophisticated, using more variations in tempo and heterophonic voices. For each group, Table I provides one example of a basic dialogue (which tended to happen in early sessions), contrasted with one of a complex dialogue (which tended to happen in later sessions).

Table I. Basic vs. complex dialogues

Groups	Basic Dialogue	Complex Dialogue
G_1	In S_1 (see video 6A) sequential call-response occurred with two textured, melodic voices (M_2, M_3) and one fixed rhythm voice (M_1). There was a lack of role change or variations in tempo. The three voices were clearly audible as separate.	In S_4 (see video 6B) the leading melodic voice was transferred from M_2 to M_1 (dynamic role change). The other two voices (M_2, M_3), which are rhythmic melodies, added counterpoint to the leading melody as call-response. There were several variations in tempo. The three voices intertwined with one another.
G_2	In S_2 (see video 6C) there were 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 was lack of gradual changes in volume. The three voices added counterpoint to one another.	In S_3 (see video 6D) there was a *crescendo* 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 added counterpoint to M_2.
G_3	In S_1 (see video 6E) sequential call-response	In S_3 (see video 6F) there were two

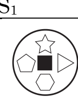
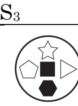
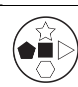
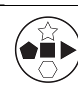
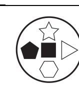
	was observed with one call high pitch melodic voice (M_3) and two response melodic voices (i.e., M_1 as mid-high pitch and M_2 as mid-low pitch). All voices combined melodic exploration with control (e.g., SGs were turned left or right yielding multiplicity of tones or rhythms, which not always combined harmonically and rhythmically).	simultaneous melodic voices – one high pitch (M_1) and one low pitch (M_2), which combined harmonically and rhythmically.
G_b	In S_2 (see video 6G) two simultaneous high pitch melodic voices (M_1 and M_2) combined with a homophonic bass/rhythmic voice (M_2). All voices combined melodic exploration with control (e.g. SGs were turned left or right yielding multiplicity of tones or rhythms, which not always combined harmonically and rhythmically).	In S_4 (see video 6H) the leading melodic voice was transferred from M_2 to M_1 (dynamic role change): first, simultaneously one high pitch melodic leading voice (M_2) combined with a low pitch melodic voice (M_1); then, simultaneously one high pitch melodic leading voice (M_1) combined with a low pitch melodic voice (M_2). All voices combined harmonically and rhythmically.

Given the time constraints in a musical improvisation session and the protocols of improvisation, participants had to coordinate what in popular and jazz music are traditionally known as intros and endings. In interaction analysis, beginnings and endings are considered meaningful units when analysing an activity as a structured sequence of events because they can tell us about collaborative negotiation during the start and end of an activity [Jordan and Henderson 1995, p. 57–59].

In later sessions, musicians tended to focus more on their individual voices during intros, 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 most groups tended to share voices in a more sophisticated way (G_1, G_3 and G_b), frequently using the middle of the table. Figure 10 illustrates the first (top) and last (bottom) intro of G_1 (see videos 7A, 7B), whereas Figure 11 illustrates the first (top) and last (bottom) ending of G_1 (see videos 8A, 8B). Both figures indicate how musically sophisticated intros and endings can become over time. For example, in intros (see Figure 10) a development of greater sophistication is shown from using one SG per thread with immediate sound output (top) in the first session 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 the last session. In endings (Figure 11), the development of greater sophistication is shown from the sequential removal of objects of individual threads (top) in the first session to voluntary serendipitous contributions to a large shared thread on the centre of the table (bottom) in the final one.

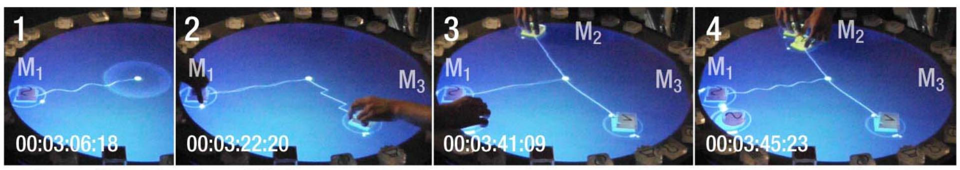
Apart from developing musical sophistication over time, when comparing groups and sessions, we found a large variety of types of endings. They included various combinations of the same set of elements (see Table II), illustrating how group dynamics and musical practices may differ even in a small set of groups.

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

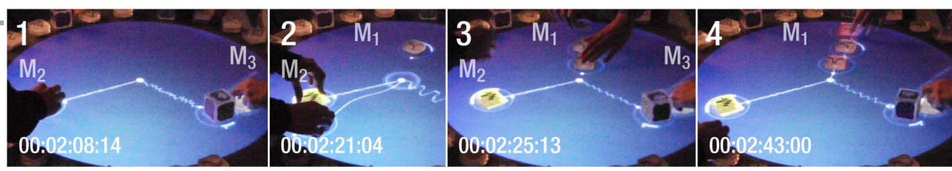
Group	S_1	S_2	S_3	S_4
G_1				
G_2				

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 of a shared thread (e.g., starting from one thread for each musician to one shared thread).

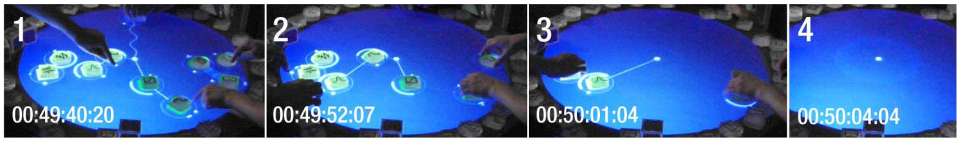


In S_1, M_1G_1 adds a first SG (frame 1). M_3G_1 adds and rotates a second SG whilst M_1G_1 changes the slider of the first SG (frame 2). M_2G_1 adds and rotates a third SG whilst M_1G_1 adds a controller to the first SG (frame 3). M_2G_1 adds a filter to the third SG while rotating both objects (frame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

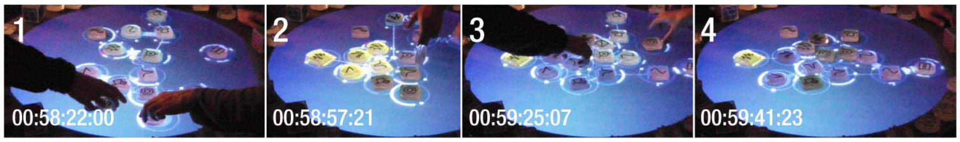


In S_4, M_3G_1 adds a cube and a programmer to select a sample and M_2G_1 adds a SG (frame 1). M_2G_1 adds a second SG and rotates one with each hand while M_1G_1 adds a FX (preview technique) (frame 2). M_3G_1 reprograms the cube, M_2G_1 removes the second SG and M_1G_1 adds two more FXs (preview technique) (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 (frames 1–3) ... until the patch is left "alive" (frame 4).

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

This data reveals that musicians' participation was egalitarian and roles were flexibly changed, which contrasts with traditional ensembles where roles are more fixed. Furthermore, groups developed their own collective, distinctive sequence of musical events using a variety of combinations of objects, which became more complex over time, and which varied depending on each group dynamics and situation.

8. FINDINGS: SOCIAL GROUP INTERACTION

In this section, we detail the results regarding social group interaction in terms of mimicking behaviours and verbal communication, which show how collaborative peer learning occurred with a hands-on approach in a situated context.

8.1 Mimicking

Mimicking refers to group members imitating another's actions or behaviours. Mimicking occurred in all groups and throughout all sessions without explicit talk. We noted that the 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.

Generally, in early sessions, musicians tended to mimic basic structures or techniques: for example, muting or unmuting a thread (G_1S_1), strobing on and off whilst twisting left and right a filter positioned at the end of the thread (G_2S_1), exploring and dragging an object on different threads (G_3S_1), or piling objects of the same shape (G_3S_2). By contrast, during the later sessions, musicians tended to mimic more complex structures or techniques, e.g. building the same complex structure such as a CT connected to an SG connected in sequence to two FXs (G_1S_3); twisting an FX affecting an SG (G_2S_3); operating two SGs simultaneously (G_3S_3); or shaking two FXs between two threads (G_3S_3).

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_2G_2 first discovers and then develops in S_1 and S_2 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 of pointing an object to the centre for a global sound effect to his repertoire. Finally, in S_4, M_1 also utilizes and develops this technique, together with M_2 and M_3, who continue to use it. Figure 13 illustrates the use of the technique by each of the three participants throughout the sessions (see videos 9A, 9B, 9C).

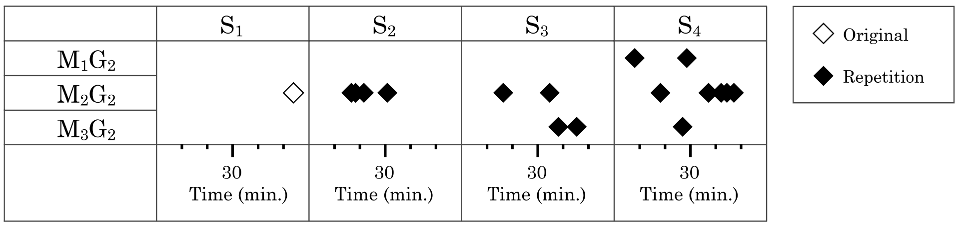
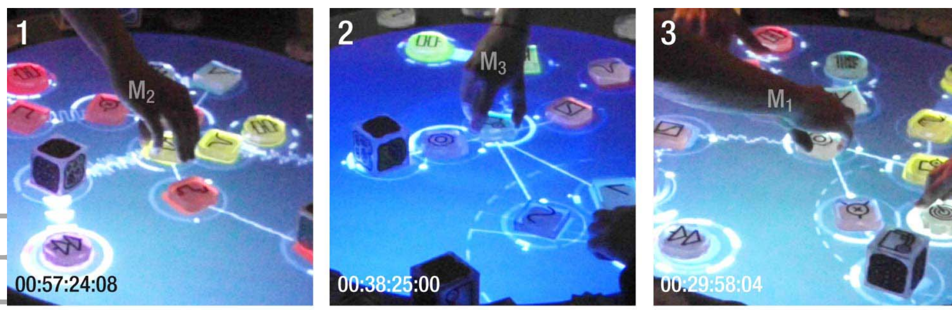


Fig. 12. Timeline visualisation of mimicking one technique over time.



In S_1, M_2G_2 operates distortion effect in the centre using strobing and twisting.

In S_3, M_3G_2 operates global feedback in the centre using strobing, twisting & dragging.

In S_4, M_1G_2 operates granulator effect in the centre first twisting it and then leaving it in the centre for 90 sec.

Fig. 13. Mimicking.

Mimicking was widely used for implicit peer learning: it allowed musicians to transfer techniques and practices between them. Mimicking occurred in a hands-on and face-to-face context of learning by doing using constructive building blocks. What specific techniques and practices were mimicked varied depending on the different group dynamics and situated contexts.

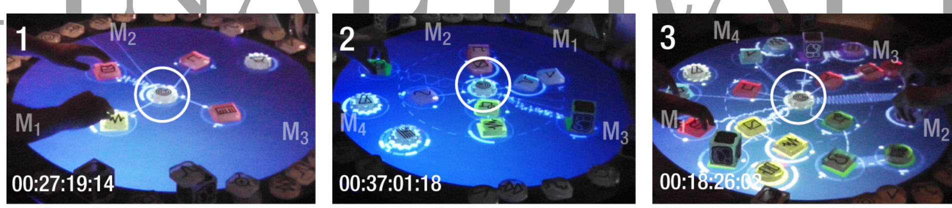
8.2 Verbal Communication

Conversations happened mostly at the beginnings and endings of the sessions, and only occasionally in the middle. Verbal communication was primarily used to share knowledge in explicit peer learning. The most common events were error/repair situations, discoveries, question/answer situations, think 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 the global volume object. This can be used to control the global volume of the Reactable by rotating the object. It also has a slider, which defines the amount of reverb or echo. However, the reverb feature is not explained in the user manual. On several occasions, by just rotating the object, the reverb was increased unexpectedly to 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 through explicit communication. We here give one example:

> In G_1, the issue arose and was repaired in S_3. M_2G_1 started the reverb situation, and immediately repaired the situation by moving the slider. Later on, M_2G_1 used it again intentionally. After the ending, M_2G_1 shared his discovery by having a group discussion with the other participants about the behaviour of the object.

There were also examples of verbal communication in particular group situations. As shown in Figure 14, 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 (see video 10A). The group discovered the object's possibilities through discussion and experimentation. The group remembered and re-used this technique in the following sessions S_3 and S_4 (see videos 10B, 10C) when they were four musicians, 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 (see video 10B). In S_4 the technique was repeated twice without the need of naming it, as part of the group repertoire: one at 00:15:42:23 (see video 10C), and the other at 00:42:37:21.



In S_2, discovery of using the radar trigger object as a 4-step sequencer (frame 1). In S_3, reuse of the radar trigger technique as a 4-step sequencer (frame 2). In S_4, again, reuse of the radar trigger technique (frame 3).

Fig. 14. Explicit peer learning.

Verbal communication was used for explicit peer learning: it was used to share knowledge in a hands-on context of learning from the peers while doing. As with mimicking, this explicit transmission of knowledge varied depending on the different group dynamics and situated contexts.

9. DISCUSSION

Here we discuss the findings relating to the interface, tangibility, and 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 finding that musicians tend to play with the objects nearest to themselves matches 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]) during 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, which indicates that they were seen as useful contributions. This concurs with Hornecker et al.'s [2008] suggestion that allowing interventions into others' spaces can promote a rich range of opportunities for collaborative work, group dynamics, and expertise development. Moreover, as Wang et al.'s [2006] suggest, having no ownership markers might support participants in feeling part of a group.

Objects with different levels of thread influence ranging from local to global seem to encourage a multiplicity of interventions into others musicians' 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 a lack of territorial constraints, as it is possible with the Reactable, raises new opportunities for group collaboration in creative activities such as musical improvisation.

Our findings suggested that Reactable's dynamic patching of automatic connections promoted serendipity and creative discovery, a mechanism that seems useful for creative domains in tabletop TUIs, especially during early exploratory phases. Such findings are in agreement with recent research on collaborative learning and interferences (Pontual Falcão and Price [2011]), where unintentional interferences are found to promote exploratory learning in more talkative contexts. Although this version of the Reactable eases access for beginners and casual users, it can also be interpreted as a constraint because automated connection 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], as newer Reactable versions have implemented, by means of physically bumping objects between them to activate or deactivate the mechanism.

9.2 Tangible Interaction

The Reactable interface is designed on a modular and constructive basis [Jordà 2008]: a set of tangible building blocks, each with a specific function that can be interconnected to create both basic and 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 manage 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 more complex behaviours at a digital level, as happens with the Reactable's dynamic patching mechanism.

Body and hand movements are characteristic of tangible and physical interaction. When using the Reactable, groups performed a range of bodily actions and hand gestures with generally little eye contact and individuals' focus being on the tabletop surface. A similar lack of eye contact has also been found in other studies of group tabletop interaction [Hornecker et al. 2008], echoing early research on video conferencing systems, which revealed that visibility of the workspace is often more important for awareness and collaboration than a 'talking heads' video [Nardi et al. 1995]. The observed coordinated bodily 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 by having a shared interface with real-time feedback, where manipulation and feedback response occur at the same space and time. This synchronicity of input and output (i.e., real-time feedback) is suggested as a design feature that supported the learning evident across the four sessions: immediate results enabled users to explore the effects of different interface 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. By contrast, with touch-based mobile devices, there is less need to interact with the body, and interactions are of a smaller scale, thus the joint action is of a different character and appears much more introverted (cf. Swift [2012]). This chimes with Jordà's [2008] description of one of the goals in the design of the Reactable's being to increase performativity in electronic music making.

We could also see how the tangible objects support performative action, for example in the strobing effect, where musicians tended to lift the object high up from the surface to then almost smack it down again, in a full-body movement that emphasised 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, a participant moving a sound effect object across the table towards another musician left his finger in a pointing gesture on it. Just touching the tangible object does not manipulate it, enabling this kind of communicative gesture, whereas purely touch-based interaction often suffers from the Midas-touch problem. As the literature on the Reactable's development highlights [Jordà 2008], tangible manipulation, when compared to touch, can free musicians' visual attention to focus, for example, on other objects, or watch 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 the tabletop TUI: a dialogue between physical explorations and real-time feedback supports discovering hidden connections between the physical and the digital. As suggested 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, contrary to other tangible systems such as Siftables [Merrill et al. 2007]. An open question is to what extent having computationally embedded tangibles 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 per object in this Reactable version), and the number of inputs and outputs (where the outputs are limited to one or none depending on the object in this Reactable version). Yet, in the broader unit generator paradigm [Roads 1996, p. 787–788], a unit generator can include 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 [6].

9.3 Tabletop Musical Improvisation

Awareness issues of who is doing what sometimes occurred when there was a lack of understanding of how to control the interface, mainly during early sessions. As an example, the preview technique shows how an understanding of control is developed over time, including awareness of individual actions. Blaine and Fels [2003] propose providing 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 sense-based perception. Thus, a possible solution to cope with awareness issues in early sessions might be to provide multimodal feedback, which seems to support different individual and group dynamics.

The 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 shows how musical tabletop design promotes 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 in our study 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

[6] Newer Reactable's versions such as the Reactable Live or the Reactable Mobile app include configuration settings and additional parameters.

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 sessions appeared to fulfill the role of resolution and wrap-up as happens in jazz musical improvisation (and, by extension, other musical genres as well). But we observed simultaneous equal participation, which is different to traditional endings of jazz solos.

Nonparticipation is traditionally associated with a passive attitude, whereas here it can constitute an active role (e.g., a set of tangibles left on the surface can keep behaving with no human intervention). Nonparticipation may occur for several different reasons: first, the available limited number of resources, the size and shape of the tabletop surface, and the number of collaborators seem to determine the performance considerably; 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 (or rather: bodily inactiveness) can be considered a positive aspect in tabletop musical improvisation.

The capacity of expressing varied sequences of musical events and combinations of objects 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 improvised sessions include a sequence of musical events with a beginning, development, and ending. The nature of the system makes each session different and difficult to reproduce. The following elements appear to be relevant to support these collective, distinctive set of musical events: 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); global control (e.g., global volume or global tempo) and 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 in varied situations for collaborative peer learning during musical improvisation on the Reactable. We found similarities and differences between groups in terms of how verbal communication was used, and of how techniques and practices were mimicked. Both occurred in a hands-on and face-to-face context of learning by doing using constructive building blocks.

Groups developed ensemble skills such as solving problems in teams, sharing limited resources, or social tinkering. This is in line with the findings of Harris et al. [2009] and Rick et al. [2011] who present interactive tabletops as suitable environments for collaborative learning. It also relates to *social constructivism* and the role of peer interaction [Vigotsky 1978], which considers learning as a collaborative process in a meaningful social context: here peers construct new meanings together in particular contexts. For example, the technique "the sync" was only co-invented and co-developed by group G_3. Both explicit and implicit peer learning occurred in the 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 this 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 G_3 was a newcomer 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 action*: action and knowledge are interrelated; collaborative learning happens in the course of action. Our findings also relate to those of Rick et al. [2011] who discuss the benefits of supporting different group dynamics when learning using 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, the context, and the technology used. Repairing the reverb situation when using the global volume exemplifies this: understanding the behaviour of this object was co-constructed in collaboration with peers, and even though it happened in all groups, each group solved it differently in their own meaningful context.

The evidence of wide use of mimicking is understandable, 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 building blocks with a higher level of abstraction that permits to use them for different purposes. An exception is Zuckerman et al. [2005]'s MiMs, a set of building blocks with a level of abstraction that permits to build different simulations such as probability distributions or dynamic behaviours. A promising area of research seems to be exploring MIMs on tabletop TUIs for educational and teaching contexts, including tangibles with multiplicity of meaning and customisation of tangibles.

9.5 Lessons Learned: Design Considerations for Hands-on Tabletop Collaborative Learning

We derive the following set of design considerations from the previous discussion on the topics that emerged from data analysis of interface, tangible, musical, and social group interactions: Reactable interface (1–2), tangible interaction (3–5), tabletop musical improvisation (6–7), and situated peer learning (8–9). These design considerations aim at informing how to better support 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) could be harmful for a free-form collaborative activity such as improvisation. The lack of territories seemed to promote a self-regulation of space, which was beneficial for musical improvisation. The nature of this self-regulation appeared to be 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. *Automated connection mechanisms can support creativity and learning*. 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 want more control over connections. In this case, an additional mechanism to manually control them seems suitable.

— 3. *Consider modularity and scalability with objects*. Our findings show that a modular tangible interface can 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 to learning through construction processes.

— 4. *Provide synchronicity in actions with objects*. The Reactable's implementation of synchronicity mechanisms (e.g., global tempo clock, real-time feedback) provided a constraint that promoted 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 during hands-on activities because bodily actions and gestures can be seen and mimicked, and practical knowledge can be transmitted by doing. These gestures require sufficient space to be performed.

— 5. *Allow real-world, multi-dimensional interactions, which also have meaning in the digital domain*. We are still in the infancy of understanding mappings between the physical and the digital domains in TUIs. The digital domain in tabletop TUIs, usually represented by real-time feedback, is often discovered via a trial and error exploration of the physical properties of the tangibles and their relations (e.g., piling or tossing objects), which can then be easily reproduced by others. The kinds of actions that users perform in this physical exploration may inform future directions of tabletop design by suggesting actions that could be digitally interpreted, going beyond the 2D mappings which are currently implemented with the Reactable.

— 6. *Provide real-time multimodal feedback and allow for new approaches to participation*. Transferring traditional creative group activities such as improvisation onto interactive tabletops presents new challenges to group collaboration (e.g., awareness issues, participation roles). Providing multimodal feedback such as touch, vision or auditory senses can mitigate awareness issues and facilitate different learning styles. Permitting flexibility in roles and participation (e.g., active nonparticipation, egalitarian participation) without disrupting the activity seems relevant here, in contrast to more fixed and hierarchical roles in traditional improvisation.

— 7. *Provide diversity and flexibility for (musical) expression and development*. A flexible and modular tabletop TUI seems to promote a variety of combinations of musical expression and control based on object manipulation. This supports a wide range of flexible, creative approaches to sequencing events.

— 8. *Allow for a variety of styles and situations*. A modular and flexible environment based on constructive building blocks seems to be suitable to support group dynamics and situated peer learning. This approach promotes different group development processes, social tinkering, and learning styles. It has no interface divisions regarding the number of users and their positions, who thus can join or leave the activity at any time; supporting different problem solving styles; or supporting different levels of composition complexity.

— 9. *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.

The implications of our study concern design, research, and education. The lessons learned listed above include a range of future directions and explorations for design. Our study further demonstrates the utility of longitudinal studies and evidences that studying musical improvisation on interactive tabletops can inform HCI research and provide insights on skill as well as group coordination and development over time. Our findings furthermore indicate how an approach based on constructive building blocks on a tabletop tangible interface supports situated group learning in hands-on activities.

9.6 Study Limitations and Future Work

A potential critique of our study may be that we studied improvisation practices in a lab instead of in 'natural settings'. As Rooksby [2013] argues, social analysis does not necessitate fieldwork (e.g., Suchman's [1987] famous study was conducted in a lab setting), and lab-based studies can provide an adequate setting for observing situated action. The musicians in our study relied largely on the same resources for establishing awareness, coordination, and for learning, as they would do in other settings. Moreover, we attempted to achieve adequate ecological validity by: (i) using a casual and relaxed setup; and (ii) working with expert musicians, who are familiar with musical improvisation, and are used to playing (and engaging) for long periods in group work, even with strangers. As we discussed earlier, the musicians' behavior (e.g., leaving the room to take phone calls, arriving late for sessions, turning the speakers' volume level up or down at will) indicates that we were successful in this. Furthermore, we studied musical improvisation, a free-form activity that includes known protocols (e.g., beginnings, endings, dialogues) that cope with playing in a group with strangers, thus providing our participants with a repertoire to draw upon. A similar in-the-wild study would be very difficult to conduct: it is unlikely that we would be able to access several bands having the same musical tabletop instrument in their studios. In addition, with growing expertise, learning and development processes slow down and become harder to observe. We would thus 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 potentially 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 the observed differences in group dynamics 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 real-world usage settings (e.g., schools or museums). Other topics could be studied in more controlled settings, which would also enable the effects of different features of the interface to be manipulated and compared. 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. It was out of the scope of this article to consider quality and progress of the musical style of the groups. Future studies on these topics could further 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 the challenges and opportunities presented by a set of constructive building blocks on a tabletop tangible interface over time. We observed interface, tangible, musical and social group interactions. 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 promoted group coordination and learning by mimicking others through instrumental interaction in a situated context. It also raised new challenges to group collaboration, concerning awareness issues or participation roles. We found that the Reactable's lack of territorial constraints and its automated connection mechanism promoted 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 potentially inform constructivist approaches to learning using a computationally enhanced tabletop environment in other domains.

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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