Tangible Around-Device Interactions for Multi-Tablet Environments to Promote Collaborative Learning

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Abstract

Collaborative serious games have been proven to have a positive impact on behavior and learning. However, the majority of these games are still being developed for traditional technological platforms, e.g., video consoles and desktop/laptop computers, which have been deemed suboptimal for children by several studies. Instead, the use of handheld devices such as tablets and smartphones presents several advantages: they are affordable, very widespread, and mobile—which enables physical activity and being able to engage in a game without requiring users to gather around a fixed, dedicated, location. Plus, combining several of these devices and coordinating interactions across them in what is called a Multi-Display Environment (MDE) brings on additional benefits to collaboration like higher scalability, awareness, parallelism, and fluidity of the interaction.

How to interact with these multi-tablet environments is therefore a critical issue. Mobile devices are designed to be interacted mainly via touch, which is very straightforward but usually limited to the small area of the displays, which can lead to the occlusion of the screen and the underuse of the peripheral space. For this reason, this thesis focuses on the exploration of another interaction mechanism that can complement touch: tangible around-device interactions. Tangible interactions are based on the manipulation of physical objects, which have an added value in childhood education as they resonate with traditional learning manipulatives and enable the exploration of the physical world. On the other hand, the exploitation of the space surrounding the displays has several potential benefits for collaborative-learning activities: reduced on-screen occlusion (which may increase workspace awareness), the use of tangible objects as containers of digital information that can be seamlessly moved across devices, and the identification of a given student through the encoding of their ID in a tangible manipulator (which facilitates the tracking of their actions and progress throughout the game).

Even though several previous works have designed multi-display collaborative games for children based on mobile devices, they seldom support multiple users performing cross-surface interactions between the devices or the use of tangible interactions.

This thesis describes two different approaches to build collaborative-learning games for MDEs using tangible around-device interactions. One, called MarkAirs, is a mid-air optical solution relying on no additional hardware besides the tablets except for several cardboard printed cards. The other, Tangibot, introduces a tangible-mediated robot and other physical props in the environment and is based on RFID technology.

Both interactions are respectively evaluated, and it is observed that MarkAirs is usable and undemanding both for adults and for children, and that fine-grained gestures above the tablets can be successfully conducted with it. Also, when applied to collaborative games, it can help reduce screen occlusion and interference among the different users' actions, which is a problem that may arise in such settings when only touch interactions are available. A collaborative learning game with MarkAirs is evaluated with primary school children, revealing this mechanism

as capable of creating collaborative learning experiences and presenting an added value in user experience, although not in performance.

With respect to Tangibot, we show how collaboratively controlling a mobile robot with tangible paddles and achieving certain precision with it is feasible for children from 3 years of age, and even for elderly people with mild cognitive impairment. Furthermore, it provides a fun experience for children and maintains them in a constant state of flow during the activities, which has been identified as promising for learning. The platform is compared to a tactile multi-tablet version, and it is observed that both versions enable good collaboration overall, with the tangible platform outperforming the tactile one in being able to make the children reach consensus after a discussion, split and parallelize work, and treat each other with more respect. Nevertheless, it is observed that the children manage their time worse with Tangibot, perhaps due to the novelty effect. These findings overall suggest that, despite the current widespread individual tablet-based learning strategies, collaborative educational technology should concentrate on collaborative games based on physical spaces and interactions.

Resumen

Diversas investigaciones han probado que los juegos serios colaborativos tienen un impacto positivo en el comportamiento y el aprendizaje. Sin embargo, la mayoría de estos juegos siguen desarrollándose para plataformas tecnológicas tradicionales como videoconsolas y ordenadores de sobremesa o portátiles, los cuales han sido identificados como sub-óptimos para niños en diversos estudios. En su lugar, el uso de dispositivos móviles como tabletas y teléfonos inteligentes presenta diversas ventajas: son económicamente asequibles, están ampliamente distribuidos, y pueden ser transportados, lo cual permite la actividad física y poder iniciar un juego sin necesitar que los usuarios se trasladen a una localización fija, especialmente dedicada para tal fin. Además, combinar varios de estos dispositivos y coordinar la interacción entre ellos en lo que se denomina Entorno Multi-Pantalla (EMP) proporciona beneficios adicionales para la colaboración tales como una mayor escalabilidad, conciencia del espacio de trabajo, paralelismo y fluidez de las interacciones.

La interacción en estos entornos multi-tableta es por tanto un aspecto crítico. Los dispositivos móviles están diseñados para ser interactuados mediante el toque de los dedos principalmente, lo cual es muy sencillo y directo, pero está normalmente limitado a la pequeña dimensión de las pantallas, lo que puede conllevar la oclusión de la pantalla y la infrautilización del espacio periférico. Por esta razón, esta tesis se centra en la exploración de otro mecanismo de interacción que puede complementar al táctil: interacciones tangibles alrededor del dispositivo. Las interacciones tangibles están basadas en la manipulación de objetos físicos, lo que presenta un valor adicional en la educación de los niños puesto que resuena con los manipulativos educativos tradicionales y permite la exploración del mundo físico. Por otra parte, la explotación del espacio que envuelve a las pantallas tiene diversos beneficios adicionales para actividades educativas colaborativas: reducida oclusión de la pantalla (lo cual puede incrementar la conciencia del espacio de trabajo), el uso de objetos tangibles como contenedores de información digital que puede ser transportada de forma continua entre dispositivos, y la identificación de un determinado estudiante a través de la codificación de su ID en un operador tangible (lo cual facilita el seguimiento de sus acciones y progreso durante el juego).

Aunque diversos trabajos previos han diseñado juegos colaborativos multi-pantalla para niños basados en dispositivos móviles, raramente dan soporte a múltiples usuarios realizando interacciones entre los dispositivos o al uso de interacciones tangibles.

Esta tesis describe dos enfoques distintos para construir juegos educativos colaborativos en EMPs utilizando interacciones tangibles alrededor de los dispositivos. Una, denominada MarkAirs, es una solución óptica aérea que no necesita ningún hardware adicional aparte de las tabletas excepto diversas tarjetas de cartón impresas. La otra, Tangibot, introduce un robot tangiblemente controlado y otro atrezo físico en el entorno, y se basa en tecnología RFID.

Ambas interacciones son respectivamente evaluadas, y se observa que MarkAirs es usable y poco exigente tanto para adultos como para niños, y que se pueden

realizar con éxito gestos de grano fino encima de las tabletas con ella. Además, al aplicarse en juegos colaborativos, puede ayudar a reducir la oclusión de las pantallas y la interferencia entre las distintas acciones de los usuarios, lo cual es un problema que puede surgir en este tipo de escenarios cuando solamente se dispone de interacciones táctiles. Se evalúa un juego educativo colaborativo con MarkAirs con niños de educación primaria, y se concluye que este mecanismo es capaz de crear experiencias de aprendizaje colaborativo y de presentar un valor añadido en términos de experiencia de usuario, aunque no en eficiencia.

Con respecto a Tangibot, se muestra que controlar colaborativamente un robot móvil mediante unas palas tangibles con cierta precisión es factible para niños a partir de los tres años de edad, e incluso para personas mayores con un deterioro cognitivo leve. Además, proporciona una experiencia divertida para los niños y los mantiene en un estado constante de *flow* durante las actividades, lo cual ha sido identificado como prometedor para el aprendizaje. Se realiza una comparación de la plataforma con una versión multi-tableta táctil, y se observa que ambas versiones proporcionan un buen nivel de colaboración en general, con la plataforma tangible superando a la táctil en ser capaz de que los niños lleguen a un consenso después de una discusión, en dividir y paralelizar el trabajo, y en tratarse unos a otros con más respeto. Sin embargo, se observa que los niños gestionan peor su tiempo con Tangibot, tal vez debido al efecto novedad. Esos resultados sugieren en general que, pese a las estrategias de aprendizaje individuales basadas en tabletas ampliamente utilizadas hoy en día, la tecnología para el aprendizaje colaborativo debería concentrarse en juegos colaborativos basados en espacios e interacciones físicas.

Resum

Diverses investigacions han provat que els jocs seriosos col·laboratius tenen un impacte positiu en el comportament i l'aprenentatge. No obstant, la majoria d'estos jocs continuen sent desenvolupats per a plataformes tecnològiques tradicionals com videoconsoles i ordinadors de sobretaula o portàtils, els quals han sigut identificats com sub-òptims per a xiquets en diversos estudis. D'altra banda, l'ús de dispositius mòbils com ara tabletes i telèfons intel·ligents presenta diversos avantatges: són econòmicament assequibles, estan àmpliament distribuïts i poden ser transportats, la qual cosa permet l'activitat física i poder iniciar un joc sense necessitat de què els usuaris es traslladen a una localització fixa i especialment dedicada per a eixa finalitat. A més, combinar diversos d'estos dispositius i coordinar la interacció entre ells en el que es denomina Entorn Multi-Pantalla (EMP) proporciona beneficis addicionals per a la col·laboració tals com una major escalabilitat, consciència de l'espai de treball, paral·lelisme i fluïdesa de les interaccions.

La interacció amb estos entorns multi-tableta és per tant crítica. Els dispositius mòbils estan dissenyats per a ser interactuats mitjançant tocs de dit principalment, mecanisme molt senzill i directe, però està normalment limitat a la reduïda dimensió de les pantalles, cosa que pot ocasionar l'oclusió de la pantalla i la infrautilització de l'espai perifèric. Per aquesta raó, la present tesi se centra en l'exploració d'un altre mecanisme d'interacció que pot complementar al tàctil: interaccions tangible al voltant dels dispositius. Les interaccions tangibles estan basades en la manipulació d'objectes físics, cosa que presenta un valor addicional en l'educació dels xiquets ja que ressona amb els manipulatius tradicionals i permet l'exploració del món físic. D'altra banda, l'explotació de l'espai que envolta a les pantalles té diversos beneficis addicionals per a activitats educatives col·laboratives: reduïda oclusió de la pantalla (la qual cosa pot incrementar la consciència de l'espai de treball), l'ús d'objectes tangibles com a contenidors d'informació digital que pot ser transportada de forma continua entre dispositius, i la identificació d'un estudiant determinat a través de la codificació de la seua identitat en un operador tangible (cosa que facilita el seguiment de les seues accions i progrés durant el joc).

Tot i que diversos treballs previs han dissenyat jocs col·laboratius multi-pantalla per a xiquets basats en dispositius mòbils, rarament donen suport a múltiples usuaris realitzant interaccions entre els dispositius o a l'ús d'interaccions tangibles.

Aquesta tesi descriu dos enfocaments distints per a construir jocs educatius col·laboratius en EMPs utilitzant interaccions tangibles al voltant dels dispositius. Una, denominada MarkAirs, és una solució òptica aèria que no precisa de cap maquinari addicional a banda de les tabletes, exceptuant diverses targetes de cartró impreses. L'altra, Tangibot, introdueix un robot controlat tangiblement i attrezzo físic addicional en l'entorn, i es basa en tecnologia RFID.

Ambdues interaccions són avaluades respectivament, i s'observa que MarkAirs és usable i poc exigent tant per a adults com per a xiquets, i que es poden realitzar gestos de granularitat fina dalt de les tabletes amb ella. A més a més, en

aplicar-se a jocs col·laboratius, pot ajudar a reduir l'oclusió de les pantalles i la interferència entre les distintes accions dels usuaris, problema que pot aparèixer en este tipus d'escenaris quan solament es disposa d'interaccions tàctils. S'avalua un joc educatiu col·laboratiu amb MarkAirs amb xiquets d'educació primària, i es conclou que aquest mecanisme és capaç de crear experiències d'aprenentatge col·laboratiu i de presentar un valor afegit en termes d'experiència d'usuari, tot i que no en eficiència.

Respecte a Tangibot, es mostra que controlar conjuntament un robot mòbil mitjançant unes pales tangibles amb certa precisió és factible per a xiquets a partir de tres anys i inclús per a persones majors amb un lleu deteriorament cognitiu. A més, proporciona una experiència divertida per als xiquets i els manté en un estat constant de *flow* durant les activitats, cosa que ha sigut identificada com a prometedora per a l'aprenentatge. Es realitza una comparació de la plataforma amb una versió multi-tableta tàctil, i s'observa que ambdues versions proporcionen un bon nivell de col·laboració en general, amb la plataforma tangible superant a la tàctil en ser capaç de què els xiquets arriben a un consens després d'una discussió, en dividir i paral·lelitzar el treball, i en tractar-se uns a altres amb major respecte. No obstant, s'observa que els xiquets gestionen pitjor el seu temps amb Tangibot, possiblement degut a l'efecte novetat. Estos resultats suggereixen en general que, malgrat les estratègies d'aprenentatge individuals basades en tabletes àmpliament esteses hui en dia, la tecnologia per a l'aprenentatge col·laboratiu hauria de concentrar-se en jocs col·laboratius basats en espais i interaccions físiques.

Keywords

Child-Computer Interaction, Mixed Reality, Computer-Supported Collaborative Learning (CSCL), Tangible User Interfaces (TUI), Multi-Display Environments (MDE), Around-Device Interactions (ADI), Tablets, Robots.

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Introduction

1.1 Motivation

Computer-Supported Collaborative Learning (CSCL) is a multidisciplinary field focused on studying how computers (or rather, technology) can assist people in educational processes to help them learn together. In the words of Stahl et al. (2006), "the idea of encouraging students to learn together in small groups has [. . .] become increasingly emphasized in the broader learning sciences. However, the ability to combine these two ideas (computer support and collaborative learning, or technology and education) to effectively enhance learning remains a challenge—a challenge that CSCL is designed to address". To better understand what CSCL consists of, it is important to differentiate between collaborative and cooperative learning. As explained by Dillenbourg (1999), "in cooperation, partners split their work, solve sub-tasks individually and then assemble the partial results into the final output. In collaboration, partners do the work 'together'." As a consequence, collaborative learning entails multiple social interactions in order to solve a given problem, such as communication, negotiation, and coordination of actions.

On the other hand, serious games have become a very popular research topic in the last decade, and have been proven to have a positive impact on behavior and learning, specifically on knowledge acquisition, content understanding, perception and cognition, affection and motivation, soft skills, and motor skills (Boyle et al., 2016; Connolly et al., 2012). Collaboration also presents a plethora of benefits for learning. Johnson and Johnson (1989) and Panitz (1999) report on more than fifty social, psychological, and academic benefits, according to the classification by Laal and Ghodsi (2012).

As previous studies reveal (Boyle et al., 2016; Connolly et al., 2012; Hainey et al., 2016), the majority of serious games are still being developed for traditional technological platforms, namely video consoles and desktop/laptop computers. These platforms, however, have several drawbacks that make them suboptimal for children. As pointed out by Nacher et al. (2015a, 2016a), they are not very intuitive; they require users to be fixed to a single location, thus preventing them from moving around and exercising; and, finally, they are essentially mono-user, which complicates the design of games to foster social abilities and collaboration.

In recent years, considerable research has highlighted the benefits of digital tabletops in education (e.g., Catala et al., 2012a,c; Dillenbourg and Evans, 2011; Reski et al., 2014; Schubert et al., 2012), including fostering creativity (Catala et al., 2012a), knowledge acquisition and transfer (Schubert et al., 2012), and, especially, collaboration (Gutwin et al., 2006; Hornecker et al., 2008; Reski et al., 2014). Their multi-touch capabilities allow more fluid (Hornecker et al., 2008) and simultaneous interactions, which lead to increased levels of parallelism and, in turn, of performance and democratized access (Rick et al., 2011). Additionally, since face-to-face settings allow users to know what the others are doing, workspace awareness is also enhanced (Gutwin and Greenberg, 2002), which facilitates the coordination of the activity (Gutwin and Greenberg, 1998). According to Hornecker et al. (2008) this awareness increases collaborative performance and leads to better results. Despite the studies that have shown these advantages, it is not common to see tabletops embedded in actual educational settings. This might be due to a number of reasons: a) their high cost; b) their form factor that prevents their use in scenarios requiring mobility and that keeps the device fixed to a single location, forcing the users to move to a specific place if they want to engage in a collaborative activity; c) their limited workspace dimensions, which can only accommodate a certain number of participants, even though it has been observed that in some scenarios the users tend to form groups dynamically—i.e., they tend to come and go (Marshall et al., 2011); and d) the fact that the interaction surface is always a public space in which some private tasks are impossible. To cope with these disadvantages and, at the same time, to take advantage of the benefits of tabletops in terms of awareness, parallelism, and fluidity of the interaction, the approach explored in this thesis is based on handheld devices. Devices such as smartphones or tablets are nowadays very affordable and commonly used. Since they are small and mobile, users are able to form improvised groups virtually anywhere. By following a "Bring Your Own Device" (Ballagas et al., 2004) scheme, it is possible to build Multi-Display Environments (MDE) to support co-located collaborative educational activities on a table-like setting by coordinating interaction across these devices. In addition, if the devices are scattered over a large area, physical activity can be encouraged, which is a key factor in children's development (Tomporowski et al., 2011) and is beneficial for supporting the construction of a positive social space for collaborative learning (Malinverni and Burguès, 2015).This would avoid the problems identified by Seitinger (2006), who points out that this type of device does not encourage full-body motion. Their size and form also allow for dynamically expanding and contracting the workspace as needed, easily done by simply adding or removing devices from the environment. Finally, mobile devices enable the synergy of public and private spaces, since switching from one to the other can be easily done by covering or tilting the device.

How to interact with these multi-tablet environments is therefore a critical issue. Mobile devices are designed to be interacted mainly via touch, which is very straightforward even to the youngest of children (Nacher et al., 2014b, 2015b).

According to Shneiderman et al. (2009), direct touch enables natural interactions for three reasons: a) the visibility of objects and actions of interest; b) the replacement of typed commands by pointing actions on the objects of interest; and c) the rapid, reversible, and incremental actions which help children to keep engaged and give them control over the technology, avoiding complex instructions that complicate the interaction. These interactions, however, are usually limited to the small area of the displays, which can lead to the occlusion of the screen and the underuse of the peripheral space. For this reason, this thesis focuses on the exploration of another interaction mechanism that can complement touch: tangible around-device interactions.

On the one hand, Tangible User Interfaces (TUI) offer interaction through the manipulation of physical objects, which have an added value in childhood education "as they resonate with traditional learning manipulatives" (Strawhacker and Bers, 2014) and enable the exploration of the physical world, which "facilitates both the acquisition of information about, and experience with, the environment, together with exploration of different combinations of information" (Price et al., 2003). On the other hand, the exploitation of the space surrounding the displays has several potential benefits for collaborative activities: first, occlusion on the screens is reduced, which improves the visualization of contents and may increase workspace awareness; second, tangible objects may be used as containers of digital information that can be seamlessly moved across devices; and finally, a tangible manipulator can encode the ID of a given student, hence facilitating the tracking of their actions and progress throughout the game.

Even though several previous works have designed multi-display collaborative games for children based on mobile devices (e.g., Luchini et al., 2002; Yuill et al., 2013)), they seldom support multiple users performing cross-surface interactions between the devices or the use of tangible interactions.

1.2 Goals and Contributions

The overall aim of this thesis is to advance in the development of collaborative learning environments that make use of widespread technology such as smartphones or digital tablets. To fulfill this goal, two different approaches are proposed to build collaborative-learning games for MDEs using around-device tangible interactions. One, called MarkAirs, is a computer-vision solution relying on no additional hardware besides the tablets except for several cardboard printed cards. The other, Tangibot, introduces a tangible-mediated robot and other physical props in the MDE and is based on RFID technology. Whereas the former is intended to support activities with many users at a time through mid-air gestures with minimal additional hardware, the latter is aimed at smaller groups, which interact with multiple physical objects and have a robot as an additional tangible companion. In both cases, interactions with the displays always occur outside the physical boundaries of the displays. These environments are designed to satisfy the following requirements:

1. Make use of affordable technology and materials to enable their implantation in actual classroom settings, namely, digital tablets, RFID tags, a Lego Mindstorms robot, cardboard cards, and props like balls, foam mats, or plastic toys.

2. Enable the definition of different educational games by, or with the assistance of, teachers. For this, the technological approaches proposed should be as generic as possible.

3. Support co-located games in which collaboration is not only encouraged, but enforced in order to successfully complete the game. This is achieved by means of technological restrictions that would prevent single players from completing certain tasks by themselves.

4. Provide a simple scalability mechanism to expand or contract the workspace as needed, simply by adding or removing tablet devices.

5. Allow for players' mobility by scattering the game's physical elements across big areas.

6. Provide intuitive and fluid interactions by means of the manipulation of tangible objects.

7. Leverage the physical space around the screens by filling it with interactive tangible elements and allowing for interactions with the devices to happen outside the displays' boundaries.

The contributions of this thesis are threefold: first, the development of the aforementioned technological platforms and their validation with users; second, the design of two collaborative-learning games using said platforms for children in primary school alongside an evaluation of user experience; and, finally, a discussion on the suitability of the technologies described to support collaborative learning through games.

1.3 Research Hypothesis

Based on the goals described above, the research hypothesis explored in this work deals not only with the technological aspects needed to build the approach, but also with the suitability of the solution for its use with primary school children in collaborative learning activities. It can be expressed as follows:

"Tangible around-device interactions on multi-tablet environments can be used effectively to build collaborative-learning games for children in primary schools, and they present an added value in terms of user experience, performance, and quality of collaboration".

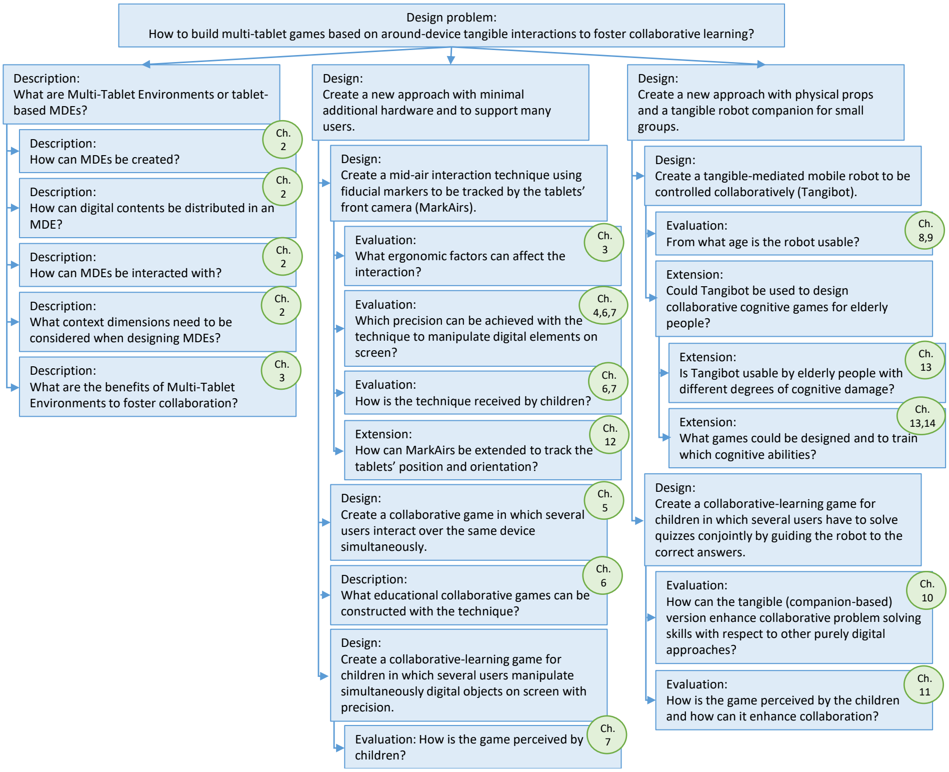

Figure 1.1: Problem decomposition (in rectangles) and the chapter they are tackled in (in circles).

1.4 Research Methodology

As stated above, this work attempts to provide two solutions based on around-device tangible interactions for MDEs to foster collaborative learning. To reach this goal, the design science research methodology was applied, as it enables the design and validation of approaches to practical problems. In the words of Hevner et al. (2004), "the design-science paradigm seeks to extend the boundaries of human and organizational capabilities by creating new and innovative artifacts". It was decided to adopt the methodological proposal by Wieringa (2009), which structures the research in nested sets of problems and tasks. As shown in Figure 1.1, this thesis is composed of different problem descriptions or discussions, artifact designs, evaluations, and extensions to the designs.

1.5 Outline of the Thesis

In order to tackle the problems described in Figure 1.1, this dissertation has been divided into four parts: one (in which this chapter is included) to state the problem to be solved and to introduce MDEs, two more to respectively describe both platforms designed (MarkAirs and Tangibot), and a fourth one to explore different extensions. A detailed description of the chapter structure is provided below:

- Part I: *Preliminaries.* Besides the present chapter, it includes in Chapter 2 the publication entitled *Toward a General Conceptualization of Multi-Display Environments* (Garcia-Sanjuan et al., 2016c).With the goal of providing a starting point for new designers of MDEs, this paper builds upon previous taxonomies on MDEs by combining them and completing them with new evidence from current practice, in order to provide a general conceptualization that explores how these environments can be created, how digital contents are distributed, how one can interact with them, and what context dimensions need to be considered. From the analysis conducted, it was observed that even though MDEs based on tablet devices have already been explored, there is a lack of studies on tangible interactions taking place around these devices, apart from the use of specific-purpose controllers such as mice or keyboards.

- Part II: *MarkAirs.* This part focuses on the design and evaluation of a mid-air interaction technique for MDEs. MarkAirs consists of several cards with fiducial markers printed on them that are recognized by the front camera of tablet devices. When in the field of view of the camera, each marker is represented on screen by a hand cursor. This cursor responds to translation and rotation movements of the card, and by performing up and down movements the hand opens or closes, respectively. This cursor can be used to “grab” digital objects on screen and manipulate some of their properties by means of certain gestures. Additionally, a “grabbed” object can be moved to other displays seamlessly by bringing the card into the field of view of the target device. This part is comprised of the following chapters:

  – Chapter 3. This contains the paper *Around-Device Interactions: A Usability Study of Frame Markers in Acquisition Tasks* (Garcia-Sanjuan et al., 2015a). This chapter explores the benefits of tabletops in face-to-face collaborative environments, as well as some of the disadvantages that prevent their implantation in real settings. Instead, the possibility of building MDEs using handheld devices is introduced, and the need to include around-device interactions is discussed. The approach presented here relies on fiducial markers being tracked by the front-camera of the devices. With the aim of obtaining preliminary insights into the usability of the technique and several ergonomic factors that can affect it, a user study with thirty-two adults is provided, focusing on the very first operation of the interaction technique: the acquisition of the marker.

- Chapter 4. This contains the publication *MarkAirs: Around-Device Interactions with Tablets Using Fiducial Markers—An Evaluation of Precision Tasks* (Garcia-Sanjuan et al., 2016a). This work contains the design of the MarkAirs interaction technique based on the results from the previous chapter, emphasizing its low-cost design and robustness before partial occlusion of the marker. Additionally, an evaluation study is reported on twenty-four users aged 14 to 60, which shows that the proposed technique is indeed feasible and that fairly precise manipulation gestures (i.e., translations, rotations, and up/down hand movements) can be made with it.
- Chapter 5. This contains the publication *Airsteroids: Re-designing the Arcade Game Using MarkAirs* (Garcia-Sanjuan et al., 2015c). This paper showcases the use of MarkAirs in a multi-display game in which several users perform concurrent manipulation of digital objects on different tablets placed on a table. Different card functionalities are introduced, namely to map the movements of the card to an object's position and orientation, to create new digital elements, and to modify properties of certain game elements. The feasibility of having multiple users interacting over the same device at the same time without interference of actions is shown, as well as the possibility of using other devices such as smartphones displaying a marker in lieu of cards.
- Chapter 6. This contains the work *MarkAirs: Are Children Ready for Marker-Based Mid-Air Manipulations?* (Garcia-Sanjuan et al., 2016d), which reports on a study similar to the one conducted in Chapter 4 on the precision primary-schooled children can achieve with MarkAirs to perform XY translations, yaw rotations and up/down gestures. More specifically, the study focuses on the precision achieved performing these gestures across different age groups both when the marker is kept steady and while in motion. This paper also includes a user experience study revealing positive impressions from the children towards the technique, and a discussion about collaborative educational games that could be conducted in an MDE using MarkAirs.
- Chapter 7 This contains the paper *Evaluation of an Educational Collaborative Game Based on Cross-Surface Interactions with Fiducial Markers for Children in Primary School*, which includes two studies. One to evaluate the feasibility and usability of MarkAirs to perform precise gestures across different age groups, as in Chapter 6, but this time focusing on performing each manipulation (i.e., translation, rotation, or scaling via up/down hand movements) either in isolation or combined. The other study, to evaluate the user experience and the ease of use and performance of the interaction technique in the context of an actual collaborative educational game in a real classroom.

- Part III: *Tangibot*. This part focuses on the design and evaluation of the around-device interaction technique for MDEs based on having a robot as a companion and other physical props as elements to interact with. RFID technology is used to provide the robot with input. Its movements (go forward, stop, turn right, turn left) are controlled by some physical paddles that are distributed among the students to enforce coordination of actions and collaboration. Several objects as well as the different tablets in the environment also have an RFID tag attached underneath that allow the robot to detect them when in close proximity. This way, interaction takes place around the device by controlling the robot and bringing it close to the other interactive elements, while tablets react to different events by populating their screens with digital contents. The different chapters that comprise this part are described below:

  – Chapter 8. This contains the publication *Design and Evaluation of a Tangible-Mediated Robot for Kindergarten Instruction* (Garcia-Sanjuan et al., 2015d).This paper presents the participatory design of the robot with teachers, and reports on the evaluation of its usability by children aged 2-4 years. The operations considered are moving the robot with the paddles collaboratively between four players, and the task, bringing the robot from point A to point B. The results indicate that these children can effectively control the robot with the tangible elements provided, and that they have fun with it.

  – Chapter 9. This contains the work *Evaluating the Usability of a Tangible-Mediated Robot for Kindergarten Children Instruction* (Nacher et al., 2016b). This paper builds upon the study described in Chapter 8 by evaluating the precision in which eighty-six children aged 2-6 are able to move the robot along a specific path while being in control of two movement commands instead of one. The results show that the youngest children are not able to control the robot successfully when certain precision in its movements is required, therefore making the platform suitable for children aged 3 or older.

  – Chapter 10. This contains the paper *Children's Acceptance of a Collaborative Problem Solving Game Based on Physical versus Digital Learning Spaces*, in which the robot's design is extended by inserting it in a multi-tablet physical environment situated on the floor, in which the robot can interact not only with the displays but also with other physical props. Following this approach, a game to foster collaborative problem solving called Quizbot is created and evaluated in terms of its acceptance by primary school children, with respect to the same game implemented in a digital tabletop and in a purely digital MDE with tablets.

  – Chapter 11. This contains the paper *Evaluating a Tactile and a Tangible Multi-Tablet Game for Collaborative Learning in Primary Education* and compares both multi-tablet versions of Quizbot presented in Chapter 10, i.e., the purely digital with tablets and the tangible one, in terms of user experience and quality of collaboration supported.

- Part IV: *Related exploratory work.* This part explores different approaches related to MarkAirs and Tangibot, in which additional uses or target population are explored. Works included in this section are still under development, but some preliminary results have already been published and are reported in the following chapters:

  - Chapter 12. This contains the publication *From Tabletops to Multi-Tablet Environments in Educational Scenarios: A Lightweight and Inexpensive Alternative* (Garcia-Sanjuan et al., 2016b). This paper introduces WeTab, a subsystem to track tablet devices in an MDE situated on a table that could be used in conjunction with MarkAirs to improve cross-surface interactions. Like MarkAirs, the additional hardware needed besides the tablet devices is minimal, consisting only of a wallpaper on the ceiling whose features are tracked by computer vision.
  - Chapter 13. This contains the work *Tangibot: A Tangible-Mediated Robot to Support Cognitive Games for Ageing People—A usability study* (Garcia-Sanjuan et al., 2017). In this chapter, Tangibot's usability by elderly people with different degrees of cognitive impairment is evaluated. In addition, a discussion is provided about its potential to design cognitive games for this population, including a collaborative one to foster creativity.
  - Chapter 14. This includes the paper *Augmented Tangible Surfaces to Support Cognitive Games for Ageing People* (Garcia-Sanjuan et al., 2015b). This work presents a prototype similar to Tangibot to create cognitive games for the elderly. In this approach, several physical tiles are arranged on a flat surface (e.g., a table), on which therapists can design collaborative games to stimulate cognitive abilities that decline with age, e.g., short-term memory. Users will then be able to modify the surface during gameplay. A mobile robot with a tablet attached moves through this surface augmenting it with visual and acoustic feedback, as well as with additional interaction capabilities via direct touch on the screen.

To sum up, the work described in this thesis has produced 13 research papers: 8 read at conferences (1 CORE A*, 2 CORE A, 3 CORE B), 2 published in scientific journals (1 JCR T1), and 3 are still under review.

Chapter 2

Toward a General Conceptualization of Multi-Display Environments

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Abstract

Combining multiple displays in the same environment enables more immersive and rich experiences in which visualization and interaction can be improved. Although much research has been done in the field of Multi-Display Environments (MDEs) and previous studies have provided taxonomies to define them, these have usually consisted of partial descriptions. In this paper we propose a general taxonomy that combines these partial descriptions and complements them with new evidences extracted from current practice. The main contribution of this paper is the summarization of the key dimensions that conform MDEs and a classification of previous studies to illustrate them.

2.1 Introduction

"Prototype tabs, pads and boards are just the beginning of ubiquitous computing. The real power of the concept comes not from any one of these devices—it emerges from the interaction of all of them" (Weiser, 1991). These visionary words by Mark Weiser revealed the promising future of combining multiple displays or screens as an active research topic, mainly due to their ability to improve system capabilities in terms of both visualization and interaction. Since then, several efforts have been made to provide a definition for working environments that involve them conjointly. These settings have been named Multi-Display Environments (MDEs) in the literature, or, more recently, Multi-Surface Environments (MSEs). Gjerlufsen et al. (2011) define them as "ubiquitous computing environments where interaction spans multiple input and output devices and can be performed by several users simultaneously." However, this definition does not require to have any surface in the environment, and emphasizes interaction being performed by several users rather than having multiple displays being accessed simultaneously. Nacenta et al. (2009), on the other hand, define them as "interactive computer system[s] with two or more displays that are in the same general space (e.g., the same room) and that are related to one another in some way such that they form an overall logical workspace." The notion of multi-person-display ecosystems provided by Terrenghi et al. (2009) is also interesting, since they include in these environments not only the screens themselves but also the space in which they are placed and the users interacting with them. Nevertheless, none of these authors include in their definitions other devices or objects used to interact with the system as part of the environment itself. Tangible interaction mechanisms based on the manipulation of physical objects is a growing body of work (Shaer and Hornecker, 2010) that makes relevant their inclusion in the definition. We therefore propose a new definition of MDE which arises from the combination of all the above; we consider as a multi-display or multi-surface environment a ubiquitous interactive computing system composed of several displays (or surfaces) with digital content that are located in the same physical space and have a "coupling" relationship to each other, the users interacting with the system, and the objects used for this purpose. The way surfaces are arranged and coupled determines how users perceive them as a whole and how interactions should happen. Coutaz et al. (2003) define coupling between surfaces by denoting their mutual dependency. Two surfaces are therefore coupled "when a change of state of one surface has an impact on the state of the other." According to this definition, the coupling would be a temporary condition between surfaces that happens when an interaction is being made, however, we would want to extend this definition to also consider different displays coupled when they have the potential of changing their mutual state, even if they are not doing so at a given moment. For this reason we adopt the definition of coupling provided by Barralon et al. (2007), who define it as an action itself or the result of said action. In the former, coupling is "the action of binding two entities so that they operate conjointly to provide a set of functions that these entities cannot provide individually." As the result of an action, "an assembly of the source entities, that is, a new compound entity that provides a new set of functions that the source entities, alone, cannot provide."

Even though multiple taxonomies for MDEs do exist, they usually offer a partial view of specific technical dimensions, such as the distribution of user interfaces among the different surfaces or the transfer of elements between them. In this paper we propose a more general taxonomy that involves how MDEs are created, how digital contents are distributed, and how one can interact with them. This taxonomy has been developed as a combination of previous ones and complemented by the analysis of MDEs found in the literature. Additionally, we provide further considerations about the context of the environment (i.e., where it is going to be implanted, by whom it is going to be used, and for what purpose) since the other technical dimensions can be affected by it. Our end goal is to provide a starting point for new designers by enabling them to identify what general key features have been tackled previously by other researchers and designers. The rest of the paper is organized as follows: Section 2.2 explores a historical review of MDEs. Section 2.3 describes previous attempts to devise frameworks and ontologies to describe these environments. Section 2.4 exposes several technical dimensions extracted from the combination of previous frameworks and the analysis of previous examples of MDEs, and a classification of these works is made according to the dimensions identified. Section 2.5 analyzes additional considerations about contexts, and our conclusions are drawn in Section 2.6.

2.2 Historical Evolution of MDEs

The first multi-display environments date back to the late 70s/early 80s, but they were known as multi-monitor environments due to the devices that comprised them. The research in this area focused on computer screens because they were the displays normally used, and they became more popular after the introduction of Apple's Macintosh II in 1987, which supported multi-monitor capacities as a standard feature. Early work on multi-monitor configurations deals mostly with visualization or control issues. Systems tackling the former are aimed at enlarging the virtual screen space (Choi et al., 2002; Cliburn, 2003; Mackinlay and Heer, 2004) or at using several monitors as peripheral spaces to be filled with auxiliary content (Grudin, 2001; Mano et al., 1981, 1982). Approaches regarding control issues are based on using a mouse to control the contents of the displays (Benko and Feiner, 2005; Richardson et al., 1998). These studies are mainly limited to single-user interaction, which severely restricts the possibility of inducing collaboration among users. Also, the coupling between the displays is configured manually through an application, which leads to static environments in which the number of devices is usually predetermined. In addition, the users are anchored to a specific position in space and cannot move, because the monitors are wired to computers which are not mobile.

In order to provide a more dynamic way to couple screens, approaches like the one by Ohta (2008) attach sensors to computer monitors and laptops. This means the devices can detect each other by proximity and do not require the user to manually configure the surfaces in the environment. This solution also allows certain mobility to the users, since laptops can be carried and they do not need to be always in the same location. However, this mobility is only possible before initiating an application in the MDE because of the proximity sensors. Once the coupling has been established, the devices must not be moved during the course of the application. Equipping surfaces with external sensors, however, can be burdensome and is not very likely to be used in actual situations with non-specialists. Fortunately, the current trend is for embedding sensors in the devices themselves. In fact, handhelds such as smartphones or tablets now have many of these sensors built in.

With the popularity of handhelds, users can still contribute their own devices to the environment, but in a more comfortable way, since these are easier to carry than laptops. Mandryk et al. (2001) studied the impressions of teenagers playing a collaborative PDA-based game. Due to the small size of the present devices, the researchers encourage the participants to form groups by putting their PDAs together to obtain a larger visualization space. The students, however, complain of not having a sense of freedom of movements, because in order to be able to work conjointly they cannot separate the screens during the activity. This kind of setup also presents visualization issues associated with the size of the displays and the large amount of space occupied by the device borders, which causes confusion and rejection in the players.

Other studies on MDEs using handheld displays go beyond considering these systems as large regular screens and focus more on interaction. Many of them especially attempt to provide techniques of sharing or transfer of elements. Some of them rely on pen-based interactions (Hinckley et al., 2004; Lyons et al., 2009; Tandler et al., 2001), others on pen-based as well as touch-based interactions (Geißler, 1998), whereas others on making gestures with the devices themselves (Hinckley, 2003; Marquardt et al., 2012). Handhelds' multi-touch capabilities enable multiuser interaction, as the users can manipulate any device in the environment regardless of the other group members.

Several authors have addressed the possibility of using gestures or interactions to establish the coupling in order to avoid having to configure it manually from an application (Hinckley, 2003; Hinckley et al., 2004; Ohta and Tanaka, 2012; Tandler et al., 2001), and some have designed geometrical arrangements of the screens (or topologies) apart from the traditional rectangle or square, even allowing a surface to leave and come back to the environment in a dynamic and simple way (Hinckley et al., 2004; Ohta and Tanaka, 2012). However, most of the previous approaches still need users to maintain their devices physically together in order to avoid losing the coupling between one another. Only a few studies, e.g., Iwai and Sato (2009); Maciel et al. (2010); Marquardt et al. (2012), or Garcia-Sanjuan et al. (2015c) allow certain movement of the devices around the environment while keeping the displays coupled. This higher mobility can lead to freer and more natural interactions but also increases the inherent complexity.

Even though some previous works support irregular topologies, they often disregard visualization, showing different views on each display (Mandryk et al., 2001; Mano et al., 1981, 1982), or they are explored in 2D (Hinckley et al., 2004; Maciel et al., 2010; Ohta and Tanaka, 2012). The few approaches that support tridimensional compositions usually rely either on sophisticated specific-purpose hardware setups like MediaShelf (Kohtake et al., 2005, 2007), or on small cubes that can be arranged in two or three dimensions to form different shapes (Goh et al., 2012; Merrill et al., 2007). However, the cubes limit interactions, since the only way to interact with them is by reorganizing them into different figures. Besides, both approaches require the surfaces to be physically attached throughout the application so as not to lose coupling. In this respect, authors like Iwai and Sato (2009) and Marquardt et al. (2012) propose element-sharing mechanisms between surfaces, relying on proximity sensors and external cameras, respectively, which allow the screens to be on different planes. These volumetric techniques support more intuitive interactions, closer to the way people behave in the real world, but they also entail design and implementation complexity issues.

Most of the approaches described above rely on having one type of device in the MDE, namely either computer screens, PDAs, tablets, etc. There has also been substantial work on MDEs combining different types of surfaces, to take advantage of the available resources in the environment (Grudin, 2001; Johanson et al., 2002; Tan et al., 2004). In fact, authors like Gjerlufsen et al. (2011) claim that supporting different kinds of displays is a requirement for a successful multi-surface application.

Besides having several surfaces with the same purpose, or having a main and secondary ones, as in Grudin (2001), this type of environment tends to favor specific functions for each type of display. As Dillenbourg and Evans (2011) point out, desktops (but also handhelds) are personal, tabletops are social, and digital whiteboards are public devices. Indeed, other authors treat small portable devices (such as smartphones or tablets) as private or personal accessories (Gjerlufsen et al., 2011; Lyons et al., 2006; Magerkurth et al., 2003; Sugimoto et al., 2004), tabletops as collaborative (Gjerlufsen et al., 2011; Sugimoto et al., 2004) and wall screens as public (Gjerlufsen et al., 2011; Magerkurth et al., 2003; Tan and Czerwinski, 2003); and, at the same time, some of these are used for visualization purposes (Lyons et al., 2006; Magerkurth et al., 2003; Rekimoto and Saitoh, 1999) and others for control (Gjerlufsen et al., 2011; Hunter et al., 2010; Sugimoto et al., 2004).

Current MDEs still have some limitations. A usual drawback is the lack of common physical or tangible objects in the interaction techniques, with a few exceptions like Kohtake et al. (2005, 2007); Rekimoto and Saitoh (1999); Sugimoto et al. (2004), which allow tangibles as information containers. This feature might enable more intuitive interactions, since people are used to manipulating physical rather than virtual objects. However, in order to track them, the designers tend to use complex hardware setups, such as ceiling-mounted cameras, which leads to complex and cumbersome configurations due to installing and calibrating this additional hardware. This also obstructs mobility and prevents multi-surface environments being formed spontaneously. Another limitation, which especially affects MDEs based on current tablets and smartphones, is the absence of peripheral interaction, since the input usually occurs within the screens themselves. This feature is important when the interaction region of the displays is limited. Additionally, since humans can only focus on a limited spatial area at a glimpse

(Smythies, 1996), having virtual content distributed among multiple displays may induce many visual attention switches, depending both on the task in hand and on the design of the input/output aspects of the system (Rashid et al., 2012).

To sum up, most of the above studies focused primarily on technical issues rather than on their possibilities of use. In fact, Yuill et al. (2013) state that, so far, little work has been conducted with tablets in group activities, and little thought has been given to their possibilities for group work, beyond the simple transfer of individual elements.

The future design of multi-surface environments will take advantage of the capabilities of handhelds like smartphones and tablets. The increasing popularity of these devices will enable users to bring their own devices together to build these environments dynamically and virtually anywhere. In order to exploit the other advantages of these surfaces, such as mobility, it would be necessary to design coupling techniques which do not require the devices to be physically attached (unless the users so desire for reasons associated with the application). Other challenges that need to be addressed are the possibility of establishing irregular, and even tridimensional, topologies, rather than the common fixed and regular (i.e., square or rectangle). Also, considering the relatively small screen dimensions of these devices, multi-surface systems should support peripheral interactions with both fingers and tangible objects. Additionally, since these setups might require the co-located participation of users, it would be necessary to take into account cultural differences and social protocols to avoid awkward situations (Hinckley et al., 2004; Terrenghi et al., 2009).

2.3 Previous Taxonomies to Describe MDEs

Several efforts have been made to describe the defining dimensions of an MDE. Some authors propose taxonomies for these terms, but they usually focus on specific features of MDEs and do not address them in a general way. Nacenta et al. (2005, 2009) thoroughly classify element transfer and interaction techniques between displays. They mostly consider mouse interactions, and note the limitations of their taxonomy when trying to classify some previous multi-display approaches. However, they provide a common vocabulary, useful for comparing different cross-device interaction techniques. Coutaz et al. (2003); Lachenal and Coutaz (2003) create an ontology aimed mainly at describing the physical properties of the individual surfaces that form the environment and specifying who conducts the interaction and how, focusing on terms such as surfaces, actors, and instruments. Additionally, Rashid et al. (2012) explore which visual arrangements of the surfaces influence visual attention switch in this kind of environment. Their taxonomy thus essentially considers visualization-related aspects. Terrenghi et al. (2009) present a more general description, which includes both social and physical dimensions, all of them arranged into three main categories: a) the size of the environment, b) the nature of social interaction, and c) the interaction technique that creates the coupling between surfaces and how elements are shared/transferred among them.

Nevertheless, none of the above give enough importance to the final use of the MDE or the users' background.

Other researchers (Gjerlufsen et al., 2011; Luyten and Coninx, 2005; Swaminathan and Sato, 1997; Tandler, 2001), although not providing a taxonomy per se, also enumerate certain requirements MDEs should fulfill, from which new dimensions can be extracted. Swaminathan and Sato (1997) discuss different types of "display configurations" (i.e., how surfaces are physically arranged in the environment and which topology they form), and also different ways of manipulating content (interaction) and other visualization issues. Others delve into more technical aspects. For instance, Luyten and Coninx (2005) explore some ways of distributing graphical elements between several displays, and Gjerlufsen et al. (2011) present some requirements for multi-surface applications and divide them into application requirements (what should they do?) and development requirements (how should they do it?).

2.4 Technical Classification of Previous MDEs

From the analysis of the above studies and building upon them, we have extracted several technical dimensions to provide a more general description of MDEs and have established a common vocabulary to serve as a summarization of previous works in the field. This section classifies these dimensions around three main axes: topology, coupling, and interaction. Concrete implementations and APIs, e.g., the ones provided by Hamilton and Wigdor (2014); Nunes et al. (2015); Yang and Wigdor (2014), have been left out of this discussion in favor of the subjacent features they enable.

2.4.1 Topology of the MDE

This section describes the dimensions relative to the physical appearance of the MDE, namely the homogeneity of the surfaces in the environment, shape regularity, spatial form, size, mobility, and scalability. Table 2.1 provides a sample of MDEs classified according to these dimensions.

Table 2.1: Selection of MDEs classified by topology dimensions.

Work	Homogeneity of surfaces	Spatial form	Shape regularity	Size	Mobility	Scalability
MDPS (Mano et al., 1981, 1982)	Homogeneous	Planar	Irregular	Yard	Fixed	Bounded
i-Land (Streitz et al., 1999)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Hyperdragging (Rekimoto and Saitoh, 1999)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
(Grudin, 2001)	Heterogeneous	Volumetric	Irregular	Yard	Fixed	Bounded
What-if (Mandryk et al., 2001)	Homogeneous	Volumetric	Irregular	Inch	Mobile	Unbounded
Connectables (Tandler et al., 2001)	Homogeneous	Planar	Regular	Foot	Mobile	Bounded

Table 2.1: Selection of MDEs classified by topology dimensions *(continued)*.

Work	**Homogeneity of surfaces**	**Spatial form**	**Shape regularity**	**Size**	**Mobility**	**Scalability**
Blinkenlights (Chaos Computer Club, 2001)	Homogeneous	Planar	Regular	Chain	Fixed	Bounded
(Choi et al., 2002)	Homogeneous	Planar	Regular	Yard	Fixed	Bounded
iRoom (Johanson et al., 2002)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Dynamic display tiling (Hinckley, 2003)	Homogeneous	Planar	Regular	Yard	Mobile	Unbounded
STARS (Magerkurth et al., 2003)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Wideband displays (Mackinlay and Heer, 2004)	Homogeneous	Planar	Regular	Yard	Fixed	Bounded
(Tan et al., 2004)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Stitching (Hinckley et al., 2004)	Homogeneous	Planar	Irregular	Foot	Mobile	Unbounded
Caretta (Sugimoto et al., 2004)	Heterogeneous	Volumetric	Irregular	Yard	Fixed	Bounded
Multi-monitor mouse (Benko and Feiner, 2005)	Homogeneous	Planar	Regular	Yard	Fixed	Bounded
MediaShelf (Kohtake et al., 2005, 2007)	Homogeneous	Volumetric	Irregular	Yard	Fixed	Bounded
CollaborationTable (Kohtake et al., 2005, 2007)	Homogeneous	Planar	Regular	Yard	Mobile	Unbounded
MUSHI (Lyons et al., 2006)	Heterogeneous	Volumetric	Irregular	Yard	Mobile	Unbounded
Perspective cursor (Nacenta et al., 2006)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Siftables, Sifteo Cubes (Merrill et al., 2007, 2012)	Homogeneous	Volumetric	Irregular	Foot	Mobile	Unbounded
(Ohta, 2008)	Homogeneous	Planar	Regular	Yard	Mobile	Unbounded
Multi-Display Composition (Lyons et al., 2009)	Homogeneous	Planar	Regular	Yard	Mobile	Bounded
CrossOverlayDesktop (Iwai and Sato, 2009)	Heterogeneous	Volumetric	Irregular	Perch	Mobile	Bounded
(Law et al., 2009)	Heterogeneous	Volumetric	Regular	Perch	Fixed	Bounded
(Maciel et al., 2010)	Homogeneous	Planar	Irregular	Yard	Fixed	Unbounded
TeleStory (Hunter et al., 2010)	Heterogeneous	Volumetric	Irregular	Yard	Fixed	Unbounded
CompUTE (Bardram et al., 2010)	Homogeneous	Planar	Regular	Yard	Mobile	Bounded
Mobile Stories (Fails et al., 2010)	Homogeneous	Planar	Regular	Inch	Mobile	Bounded
Shared substance (Gjerlufsen et al., 2011)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Bounded
Pass-them-around (Lucero et al., 2011)	Homogeneous	Planar	Regular	Yard	Mobile	Unbounded
GroupTogether (Marquardt et al., 2012)	Heterogeneous	Volumetric	Irregular	Perch	Fixed	Unbounded
Pinch (Ohta and Tanaka, 2012)	Homogeneous	Planar	Irregular	Yard	Mobile	Unbounded
i-Cube (Goh et al., 2012)	Homogeneous	Volumetric	Irregular	Foot	Mobile	Unbounded
LunchTable (Nacenta et al., 2012)	Heterogeneous	Volumetric	Regular	Perch	Fixed	Bounded
(Schmidt et al., 2012)	Heterogeneous	Volumetric	Irregular	Yard	Fixed	Unbounded
Pass the iPad (Yuill et al., 2013)	Homogeneous	Volumetric	Irregular	Yard	Mobile	Unbounded
HuddleLamp (Rädle et al., 2014)	Homogeneous	Planar	Irregular	Yard	Mobile	Unbounded
Conductor (Hamilton and Wigdor, 2014)	Heterogeneous	Volumetric	Irregular	Perch	Mobile	Unbounded

Table 2.1: Selection of MDEs classified by topology dimensions *(continued)*.

Work	Homogeneity of surfaces	Spatial form	Shape regularity	Size	Mobility	Scalability
TACTIC (Nunes et al., 2015)	Heterogeneous	Volumetric	Irregular	Yard	Fixed	Bounded
Airsteroids (Garcia-Sanjuan et al., 2015c)	Homogeneous	Planar	Irregular	Yard	Mobile	Unbounded
WeTab (Garcia-Sanjuan et al., 2016b)	Homogeneous	Planar	Irregular	Yard	Mobile	Unbounded

Homogeneity of Surfaces

When composing multi-surface environments, the several devices involved can essentially be the same or have similar features (e.g., computers and laptops—Benko and Feiner, 2005; Mackinlay and Heer, 2004—, smartphones and tablets—Garcia-Sanjuan et al., 2015c; Lucero et al., 2011—, etc.) or can be significantly different (e.g., tablets and wall screens—Marquardt et al., 2012—, tabletops and PDAs—Sugimoto et al., 2004—, etc.). Such (dis)similarity can be seen as whether the environment supports either *homogeneous* or *heterogeneous* devices. According to this, homogeneous environments are settings where all devices have similar size, technology, and interaction methods (see Figure 2.1), whereas heterogeneous environments are composed of displays of different shape, proportions, or even purpose (see Figure 2.2).

Spatial Form

MDEs are built by putting several displays in the same physical space. The way these devices are placed determines the spatial form of the environment, which can be either *planar* (see Figure 2.1) or *volumetric* (see Figure 2.2). The former are usually the traditional flat configurations formed by either computer screens

Figure 2.1: Example of MDE with homogeneous, planar, irregular, and yard topology (extracted from Garcia-Sanjuan et al., 2015a).

Figure 2.2: Example of MDE with heterogeneous, volumetric, regular, and perch topology; and with redundant logical view (extracted from Gjerlufsen et al., 2011).

(Mackinlay and Heer, 2004; Ohta, 2008) or mobile devices (Hinckley et al., 2004; Lucero et al., 2011) aimed at enlarging the visualization space of a single screen. On the other hand, volumetric forms take advantage of the third dimension in space and are usually achieved by combining heterogeneous displays (Nacenta et al., 2006; Sugimoto et al., 2004), homogeneous environments where visualization plays a minor role (Mandryk et al., 2001; Yuill et al., 2013), or devices specifically designed for this purpose (Kohtake et al., 2007; Merrill et al., 2007).

Regularity of Shape

Regardless of the spatial form of an MDE, the regularity of its shape decides whether the different surfaces are always put together the same way or whether they can support different arrangements. We differentiate between *regular* (see Figure 2.2) and *irregular* (see Figure 2.1) shapes. Regular-shaped MDEs usually are for the purpose of extending the visualization space and often present the typical rectangular form of a planar single screen (Bardram et al., 2010; Tandler et al., 2001), or the classic "L" shape of heterogeneous environments with a wall screen next to a tabletop (Nacenta et al., 2012). Irregular shapes, on the other hand, allow flexible configurations where the users can place the surfaces arbitrarily, and are present in many environments involving mobile devices that are not aimed at extending the visualization space, since they can be moved around and placed wherever the user pleases (Iwai and Sato, 2009; Mandryk et al., 2001); or in environments with a mechanism to track all the surfaces in real time (Garcia-Sanjuan et al., 2016b; Maciel et al., 2010; Rekimoto and Saitoh, 1999), so that all of them can maintain the coupling regardless of where they are placed. There are other examples of MDEs with irregular shapes that do try to extend the visualization space and rely on proximity sensors to keep the devices coupled (Goh et al., 2012; Ohta and Tanaka, 2012).

Figure 2.3: Example of MDE with homogeneous, planar, regular, and inch topology (extracted from Fails et al., 2010).

Size

Terrenghi et al. (2009) classify MDEs by size in order to study the impact of this characteristic on the users' visual attention. They associate size with the type of movement the users must perform to see the whole visualization space. As the ecosystem gets bigger and bigger, one could expect less attention. The different sizes considered by the authors are the following:

- *Inch* (e.g., a smartphone-sized region—Fails et al., 2010): The users do not need to move their eyes (see Figure 2.3).

- *Foot* (e.g., a region the size of a laptop or a tablet—Merrill et al., 2007): The users can sight the entire workspace by moving their eyes (see Figure 2.4).

- *Yard* (e.g., a table-sized region—Garcia-Sanjuan et al., 2015c): The users must move their head (see Figure 2.1).

- *Perch* (e.g., a room—Magerkurth et al., 2003): The users must move their head as well as their body sometimes (see Figure 2.2).

- *Chain* (bigger spaces, >5m—Chaos Computer Club, 2001): The users must move their body (see Figure 2.5).

Even though this consideration might suggest that users suffer poorer visual attention as the size of the environment increases, this would not necessarily be a drawback, since bigger ecosystems could allocate more users, as pointed out by Terrenghi et al., or it simply would not matter regarding the purpose of the system (e.g., in an MDE to foster mobility and physical exercise).

Figure 2.4: Example of MDE with homogeneous, volumetric, irregular, foot, mobile, and unbounded topology; and with discrete logical view (extracted from Merrill et al., 2007).

Figure 2.5: Example of MDE with homogeneous, planar, regular, chain, fixed, and bounded topology; and with extended-continuous logical view (extracted from Chaos Computer Club, 2001).

Mobility

Depending on the particular devices used to build an MDE, the resulting space can be *fixed* (see Figure 2.5) or *mobile* (see Figure 2.4). A fixed environment, e.g., one involving desktop PCs (Choi et al., 2002), tabletops and wall screens (Nacenta et al., 2012), or complex additional hardware (Marquardt et al., 2012), cannot be moved easily from one place to another, hence preventing the users to engage in an activity in an improvised way virtually anywhere. On the other hand, using other mobile devices, e.g., laptops (Bardram et al., 2010) or tablets (Yuill et al., 2013) would allow building mobile environments following a "Bring Your Own Device" (Ballagas et al., 2004) scheme, where each user offered his own surface to the environment.

Scalability

Scalability refers to the ability of the environment to grow as required. We differentiate between *bounded* (see Figure 2.5) and *unbounded* (see Figure 2.4) topologies. Bounded MDEs have a certain number of predefined surfaces and do not provide the ability to add any more in real time (Benko and Feiner, 2005; Gjerlufsen et al., 2011), whereas unbounded MDEs allow the size of the working space to be enlarged as needed (Goh et al., 2012; Rädle et al., 2014). Depending on its degree of scalability, an MDE can allocate more or less users. In the end, the number of participants of an activity should depend on its purpose, but having an unbounded system would always provide more freedom to designers. Nevertheless, scalability is tightly related to mobility, since environments relying on mobile devices are expected to be more easily scalable.

2.4.2 Surface Coupling in the MDE

The present section explains the dimensions relative to the coupling between surfaces to build an MDE, which are the creation, mutability, logical view of each group of surfaces, and privacy. Table 2.2 classifies a selection of MDEs according to these dimensions.

Table 2.2: Selection of MDEs classified by coupling dimensions.

Work	Creation	Mutability	Logical view of each group of surfaces	Privacy
MDPS (Mano et al., 1981, 1982)	Manual	Static	Discrete, redundant	Personal
i-Land (Streitz et al., 1999)	Manual	Static	Discrete, extended-continuous	Private, personal, public
Hyperdragging (Rekimoto and Saitoh, 1999)	Assisted	Dynamic	Discrete, extended-continuous	Private, personal, public
(Grudin, 2001)	Manual	Static	Discrete	Private, personal
What-if (Mandryk et al., 2001)	Assisted	Dynamic	Discrete	Private, personal
Connectables (Tandler et al., 2001)	Assisted	Static	Extended-continuous	Public

Table 2.2: Selection of MDEs classified by coupling dimensions *(continued)*.

Work	Creation	Mutability	Logical view of each group of surfaces	Privacy
Blinkenlights (Chaos Computer Club, 2001)	Manual	Static	Extended-continuous	Public
(Choi et al., 2002)	Manual	Static	Extended-continuous	Public
iRoom (Johanson et al., 2002)	Manual	Static	Discrete, redundant, extended-continuous	Private, personal, public
Dynamic display tiling (Hinckley, 2003)	Assisted	Static	Extended-continuous	Public
STARS (Magerkurth et al., 2003)	Manual	Static	Discrete	Private, personal, public
Wideband displays (Mackinlay and Heer, 2004)	Manual	Static	Extended-continuous	Personal
(Tan et al., 2004)	Manual	Dynamic	Discrete, redundant	Private, public
Stitching (Hinckley et al., 2004)	Assisted	Static	Discrete	Public
Caretta (Sugimoto et al., 2004)	Assisted	Dynamic	Discrete	Private, public
Multi-monitor mouse (Benko and Feiner, 2005)	Manual	Static	Discrete, redundant, extended-continuous	Personal
MediaShelf (Kohtake et al., 2005, 2007)	Assisted	Static	Discrete	Public
CollaborationTable (Kohtake et al., 2005, 2007)	Assisted	Static	Discrete, extended-continuous	Private, public
MUSHI (Lyons et al., 2006)	Manual	Dynamic	Discrete	Private, public
Perspective cursor (Nacenta et al., 2006)	Manual	Static	Extended-discontinuous	Personal, public
Siftables, Sifteo Cubes (Merrill et al., 2007, 2012)	Assisted	Static	Discrete, extended-continuous	Public
(Ohta, 2008)	Assisted	Static	Extended-continuous	Personal, public
Multi-Display Composition (Lyons et al., 2009)	Manual	Static	Extended-continuous	Personal
CrossOverlayDesktop (Iwai and Sato, 2009)	Assisted	Static	Discrete	Private, personal, public
(Law et al., 2009)	Manual	Static	Extended-continuous, extended-discontinuous	Public
(Maciel et al., 2010)	Automatic	Dynamic	Extended-continuous, extended-discontinuous	Public
TeleStory (Hunter et al., 2010)	Assisted	Static	Discrete	Public
CompUTE (Bardram et al., 2010)	Manual	Static	Extended-continuous	Public
Mobile Stories (Fails et al., 2010)	Assisted	Static	Discrete, extended-continuous	Personal
Shared substance (Gjerlufsen et al., 2011)	Manual	Static	Discrete, redundant, extended-continuous	Private, public
Pass-them-around (Lucero et al., 2011)	Assisted	Static	Discrete, extended-continuous	Private, personal, public
GroupTogether (Marquardt et al., 2012)	Automatic	Dynamic	Discrete, redundant, extended-continuous	Private, personal, public
Pinch (Ohta and Tanaka, 2012)	Assisted	Static	Extended-continuous	Public
i-Cube (Goh et al., 2012)	Assisted	Static	Discrete	Public
LunchTable (Nacenta et al., 2012)	Manual	Static	Redundant	Public
(Schmidt et al., 2012)	Assisted	Dynamic	Discrete, redundant	Private, personal, public
Pass the iPad (Yuill et al., 2013)	Implicit	Dynamic	Discrete	Personal
HuddleLamp (Rädle et al., 2014)	Assisted	Dynamic	Discrete, extended-continuous, extended-discontinuous	Private, personal, public
Conductor (Hamilton and Wigdor, 2014)	Assisted	Dynamic	Discrete, redundant, extended-continuous	Private, personal

Table 2.2: Selection of MDEs classified by coupling dimensions *(continued)*.

Work	Creation	Mutability	Logical view of each group of surfaces	Privacy
TACTIC (Nunes et al., 2015)	Automatic	Dynamic	Discrete	Public
Airsteroids (Garcia-Sanjuan et al., 2015c)	Implicit	Dynamic	Discrete	Public
WeTab (Garcia-Sanjuan et al., 2016b)	Automatic	Dynamic	Discrete, extended-continuous, extended-discontinuous	Private, personal, public

Creation

In order to allow the different surfaces in the environment to share information, they must be coupled to one another. Terrenghi et al. (2009) write about "the type of interaction technique that enables the coupling of displays and transfer of interface elements across displays," and classify this into three categories: synchronous human movement—the user performs a certain gesture with the surfaces, e.g., bring them closer (Hinckley, 2003), shake them together (Holmquist et al., 2001), etc.—, continuous action—the user performs a continuous gesture like pick & drop (Rekimoto, 1997) or pinch (Ohta and Tanaka, 2012)—, and action and infrastructure—the user configures the coupling explicitly from another device—. Similarly, Barralon et al. (2007) propose several coupling mechanisms such as proximity interaction, synchronous gestures, or physical connection. However, these are more like specific techniques than a categorization. In this respect, Luyten and Coninx (2005) describe several features to design interfaces for Distributed Interaction Spaces (interfaces distributed among several devices). According to them, the interface distribution can be performed manually (the user indicates which devices they want to join) or automatically (the system does it by itself when a discovery service detects the devices in the environment). In our opinion, performing the interface distribution is a secondary step after performing the coupling between the devices, hence, combining the previous classifications, we classify the different ways of establishing the coupling into four broad categories, depending on the degree of involvement of the user: *implicit*, *manual*, *assisted*, and *automatic*. An implicit creation of the coupling means that the devices are completely unaware of one another, but the activity being carried out involves working with several surfaces at the same time as if they were exchanging information (Garcia-Sanjuan et al., 2015c; Yuill et al., 2013), hence, it is a sort of coupling that do not involve any link whatsoever among the surfaces but still provides the illusion of being connected; manual creation requires the user to explicitly set which devices are going to be part of the environment and where they are going to be located in the physical space (Grudin, 2001; Lyons et al., 2006); an assisted one also requires the action of the user, but they are only required to perform a gesture indicating they want to couple two or more devices together (Hunter et al., 2010; Tandler et al., 2001); and, finally, an automatic creation is completely transparent to the user and relies on a discovery service to determine which devices should be coupled (Garcia-Sanjuan et al., 2016b; Maciel et al., 2010; Marquardt et al., 2012).

Whereas the first and the last methods may be more comfortable for the user, the other two involve a component of intentionality that can be useful in some contexts.

Mutability

This dimension refers to both the ability to add and remove new surfaces to the MDE as well as allowing the existing devices to move inside the environment, and having the system automatically adapt to the new situation. In a *static* coupling, the devices are required to stay in the same location as they were when the coupling was first made, and they cannot be moved around without losing the coupling or entering into an inconsistent state (Mano et al., 1981; Ohta and Tanaka, 2012). This definition is similar to the "fixed" coupling from Terrenghi et al. (2009), in which "displays are tightly connected but do not allow any dynamic configuration or easy re-configuration." In contrast, a *dynamic* coupling allows for more freedom of movements since users can change the devices and/or move them around (Garcia-Sanjuan et al., 2016b; Tan et al., 2004), and it is similar to what Gjerlufsen et al. (2011) call "flexibility," to the "continuous distribution" from Luyten and Coninx (2005), or the "fluid-middle" and "loose" coupling from Terrenghi et al. (2009). Dynamic coupling implies an irregular shape, because being able to move surfaces within the environment inevitably changes the shape of the topology of the surfaces.

Logical View of Each Group of Surfaces

When several surfaces are included in the same environment, they can communicate with one another and also display the contents of a logical workspace, either totally or partially. If each surface visualizes its own contents, which are different from the other devices, we say it displays a *discrete* logical view, e.g., Magerkurth et al. (2003); Mandryk et al. (2001) (see Figure 2.4). However, if two or more devices display partial or total views of the same workspace, we can classify the logical view of those surfaces into three groups: a) *redundant* (see Figure 2.2), b) *extended-continuous* (see Figure 2.5), and c) *extended-discontinuous* (see Figure 2.6). A redundant logical view entails having the same workspace replicated on several surfaces, each of them showing the same contents although they can be graphically represented differently due to different screen sizes, resolutions, viewports, etc. (Johanson et al., 2002; Nacenta et al., 2012). In an extended-continuous logical view, the workspace is shown entirely across several surfaces, with no "empty" spaces, although the surfaces do not necessarily need to be physically joint (Lucero et al., 2011; Ohta, 2008). In contrast, an extended-discontinuous logical view allows several surfaces to represent partial views of the same workspace, but the latter does not need to be shown completely, i.e. there can be empty regions (Maciel et al., 2010; Nacenta et al., 2006). It is important to note that not all the surfaces belonging to the same environment have to support

Figure 2.6: Example of MDE with homogeneous, planar, and irregular topology; and with extended-discontinuous logical view (extracted from Garcia-Sanjuan et al., 2016b).

the same view; instead, there can be several workspaces that are visualized by one or many tablets and in a discrete, redundant, or extended view.

Similarly, other authors propose alternative classifications related to this dimension. Swaminathan and Sato (1997) consider "display configurations." If the surfaces are physically joint, the configurations can be distant-contiguous or desktop-contiguous depending on whether they are located far away or near the user, respectively. If the devices are physically separated from one another, the configuration is noncontiguous, which is similar to our extended logical view, which can be continuous or separated (discontinuous). We decided to split this dimension by considering the physical component in the spatial form and shape regularity dimensions, and how the logical workspace is visualized in this dimension.

Coutaz et al. (2003) and Rashid et al. (2012) describe compatibility modes and content coordination, respectively, between the surfaces in the environment, focused on the visualization of contents. They also consider redundancy (Coutaz et al., 2003)—a.k.a., cloned coordination (Rashid et al., 2012)—when two displays show the exact same graphical components. However, Coutaz et al. (2003) consider as a different mode, called equivalency, when two displays show the same information but due to different screen sizes or resolutions the contents are displayed differently (e.g., a form in a tabletop is displayed differently than in a smartphone). However, our classification focuses more on the information displayed than on how that information is arranged in one display or another to improve visualization. Hence, if two screens essentially visualize the same contents, we say they work in redundancy mode. Coutaz et al. also consider two more modes: complementarity (called coordinated coordination by Rashid et al.) and assignment. In both modes each surface shows different graphical elements. The difference between the two emerges from the task being carried out. Several surfaces working in complementarity mode share the same purpose or tasks, and some displays act as controllers for others, whereas in assignment mode each surface performs its own tasks. Additionally, Rashid et al. describe extended coordination, which is similar to ours, although they do not discriminate between whether there are "empty" spaces between the surfaces or not.

Privacy

Shen et al. (2003) identify three types of space in a mono-surface environment: *private*, where data is not visible or accessible to others; *personal*, where information can be visible to others but not accessible; and *public*, where everything is available to all users. This categorization can be applied to MDEs, where some particular devices in some situations may be private and others become personal or public, depending on the context of the application. Hence, the different environments can be classified according to which space(s) they allow to be formed. Because of their form, tabletops usually enable personal and public spaces (Johanson et al., 2002; Nacenta et al., 2006); wall-screens, public (Chaos Computer Club, 2001; Kohtake et al., 2005); and handhelds, private (Streitz et al., 1999; Sugimoto et al., 2004). However, when multiple mobile devices are coupled to one another in an MDE, they often allow personal (Mandryk et al., 2001) or public (Garcia-Sanjuan et al., 2015c) regions to be created.

A similar classification is made by Luyten and Coninx (2005), but they only consider personal distributed interaction spaces if only one person is allowed to interact with the system, or collaborative if multiple users can.

2.4.3 Interaction with the MDE

This section deals with interaction with the MDE once the surfaces have been coupled. The dimensions identified are interaction availability, input directness, interaction medium, interaction instruments, and input continuity. Table 2.3 shows several example MDEs classified according to these dimensions.

The classification described here intends to provide a general panorama of the key issues that must be tackled regarding interaction when building an MDE. Interested readers can consult Nacenta et al. (2005, 2009) for more detailed taxonomies concerning particular aspects associated with input, such as object movement across displays.

Table 2.3: Selection of MDEs classified by interaction dimensions.

Work	Interaction availability	Input directness	Interaction medium	Interaction instruments	Input continuity
MDPS (Mano et al., 1981, 1982)	Partial	Indirect	Around-device	Tangible-specific	Punctual
i-Land (Streitz et al., 1999)	Total	Direct, indirect	On-device	Hand-based, tangible-specific, tangible-generic	Punctual

Table 2.3: Selection of MDEs classified by interaction dimensions *(continued)*.

Work	**Interaction availability**	**Input directness**	**Interaction medium**	**Interaction instruments**	**Input continuity**
Hyperdragging (Rekimoto and Saitoh, 1999)	Total	Indirect	On-device	Tangible-specific, tangible-generic	Punctual
(Grudin, 2001)	Partial	Direct, indirect	On-device, around-device	Tangible-specific	Punctual
What-if (Mandryk et al., 2001)	Total	Direct	On-device	Hand-based, tangible-specific	Punctual
Connectables (Tandler et al., 2001)	Total	Direct	On-device	Tangible-specific	Punctual, gestural
Blinkenlights (Chaos Computer Club, 2001)	Partial	Indirect	Around-device	Tangible-specific	Punctual
(Choi et al., 2002)	Inexistent	N/A	N/A	N/A	N/A
iRoom (Johanson et al., 2002)	Total	Direct, indirect	On-device, around-device	Hand-based, tangible-specific	Punctual
Dynamic display tiling (Hinckley, 2003)	Total	Direct	On-device	Surface-based	Punctual
STARS (Magerkurth et al., 2003)	Partial	Direct	On-device	Hand-based, tangible-generic	Punctual
Wideband displays (Mackinlay and Heer, 2004)	Inexistent	N/A	N/A	N/A	N/A
(Tan et al., 2004)	Total	Indirect	On-device, around-device	Tangible-specific	Punctual
Stitching (Hinckley et al., 2004)	Total	Direct	On-device	Tangible-specific	Gestural
Caretta (Sugimoto et al., 2004)	Total	Direct	On-device	Tangible-specific, tangible-generic	Punctual
Multi-monitor mouse (Benko and Feiner, 2005)	Total	Indirect	Around-device	Tangible-specific	Punctual
MediaShelf (Kohtake et al., 2005, 2007)	Total	Direct	On-device	Hand-based, tangible-generic	Punctual
CollaborationTable (Kohtake et al., 2005, 2007)	Total	Direct	On-device	Hand-based	Punctual
MUSHI (Lyons et al., 2006)	Partial	Direct	On-device	Tangible-specific	Punctual
Perspective cursor (Nacenta et al., 2006)	Total	Indirect	Around-device	Tangible-specific	Punctual
Siftables, Sifteo Cubes (Merrill et al., 2007, 2012)	Total	Direct	On-device	Surface-based	Punctual, gestural
(Ohta, 2008)	Total	Direct	On-device	Tangible-specific	Punctual
Multi-Display Composition (Lyons et al., 2009)	Total	Direct	On-device	Tangible-specific	Punctual
CrossOverlayDesktop (Iwai and Sato, 2009)	Total	Direct	On-device	Tangible-specific	Punctual
(Law et al., 2009)	Partial	Direct	On-device	Foot-based	Punctual
(Maciel et al., 2010)	Total	Direct	On-device	Tangible-specific	Punctual
TeleStory (Hunter et al., 2010)	Total	Direct	On-device, around-device	Surface-based, tangible-specific	Punctual
CompUTE (Bardram et al., 2010)	Partial	Indirect	On-device, around-device	Tangible-specific	Punctual
Mobile Stories (Fails et al., 2010)	Total	Direct	On-device	Tangible-specific	Punctual

Table 2.3: Selection of MDEs classified by interaction dimensions *(continued)*.

Work	Interaction availability	Input directness	Interaction medium	Interaction instruments	Input continuity
Shared substance (Gjerlufsen et al., 2011)	Total	Direct, indirect	On-device, around-device	Hand-based, tangible-specific	Punctual
Pass-them-around (Lucero et al., 2011)	Total	Direct, indirect	On-device	Hand-based	Punctual, gestural
GroupTogether (Marquardt et al., 2012)	Total	Direct	On-device, around-device	Hand-based, surface-based	Punctual, gestural
Pinch (Ohta and Tanaka, 2012)	Total	Direct	On-device	Hand-based	Punctual, gestural
i-Cube (Goh et al., 2012)	Total	Direct	On-device	Surface-based	Punctual
LunchTable (Nacenta et al., 2012)	Total	Direct, indirect	On-device	Hand-based	Punctual
(Schmidt et al., 2012)	Total	Direct, indirect	On-device	Hand-based, tangible-generic	Punctual, gestural
Pass the iPad (Yuill et al., 2013)	Total	Direct	On-device	Hand-based	Punctual
HuddleLamp (Rädle et al., 2014)	Total	Direct	On-device, around-device	Hand-based, tangible-specific	Punctual, gestural
Conductor (Hamilton and Wigdor, 2014)	Total	Direct, indirect	On-device	Hand-based	Punctual
TACTIC (Nunes et al., 2015)	Total	Direct	On-device, around-device	Hand-based, surface-based, tangible-generic	Punctual, gestural
Airsteroids (Garcia-Sanjuan et al., 2015c)	Total	Direct	Around-device	Tangible-generic	Punctual, gestural
WeTab (Garcia-Sanjuan et al., 2016b)	Total	Direct, indirect	On-device, Around-device	Hand-based, tangible-generic	Punctual, gestural

Interaction Availability

Interaction availability refers to the capacity of the MDE to support interaction. It can be *inexistent*, *partial*, or *total*. If the different screens are used only for visualization or computation purposes, then we say the interaction availability is inexistent, as in Choi et al. (2002). A partial availability is present if only some of the screens allow (Bardram et al., 2010) or are used (Chaos Computer Club, 2001) for interaction at a given moment, whereas the interaction availability is total if all surfaces can be (and will be) interacted with (Hinckley et al., 2004). It is important to note the importance of context (explained below, in Section 2.5) to this dimension, since it is not enough to have individual displays supporting interaction to have interaction available in the environment; it also depends on the purpose of the activity being carried out.

We do not consider in this dimension whether multiple interactions can be performed at the same time because that would be a feature of each particular surface belonging to the environment (e.g., multi-touch capabilities in tablets). Instead, we focus only on interactions in the global multi-display space.

Input Directness

Depending on whether the user performs an action inside the boundaries of the same surface the interaction is directed to (Tandler et al., 2001; Yuill et al., 2013) or outside—e.g., by handling a pointer (Benko and Feiner, 2005; Tan et al., 2004)—, the input modality can be *direct* or *indirect*, respectively. Although direct input can be more intuitive and natural (Shneiderman et al., 2009), indirect input presents the advantage of being able to reach distant targets, which is a very frequent need in highly integrated collaborative scenarios, according to Gutwin et al. (2006).

Rashid et al. (2012) provide a similar definition of input directness, but these authors do not attempt to describe interaction with MDEs in general, but with the graphical interfaces distributed among them, putting special emphasis on visual feedback, which may not be required in some contexts.

Swaminathan and Sato (1997) also consider input as a relevant dimension under the name "pointer movement and control," which can be classified into a) direct manipulation, b) nonlinear mapping with sticky controls, and c) dollhouse metaphor. Their direct manipulation refers to the situation where, either by using fingers or laser pointers, "the user can directly point to any object in the display without having to move the pointer from a 'current' position to the object." To differentiate between direct input from the others, this definition puts the emphasis on not having to move a pointer. Technically, using fingers and laser pointers also require moving them to the desired location; the only difference being that they do not have a constant representation on the screen (as opposed to, for instance, a mouse pointer). Nonlinear mapping with sticky controls refers to speeding up the cursor when it moves through empty spaces and slowing it down near controls, thereby allowing the user to reach the whole environment with a single gesture. This feature, although interesting, is too specific for our purposes. Finally, the dollhouse metaphor, considered by these authors as the most promising, consists of a representation of the target display on another's, smaller, screen, and map the manipulations performed on the small one to the former. Again, this metaphor is interesting but it is too specific and could be seen as a particular indirect input technique according to our classification.

Interaction Medium

This category is concerned about where the interaction takes place, either *on-device* or *around-device*. The former considers interactions made on a device, either directly on the target (Hinckley et al., 2004; Ohta and Tanaka, 2012) or indirectly on another device (Rekimoto and Saitoh, 1999; Schmidt et al., 2012). It considers interactions performed on interactive surfaces like tablets or tabletops, but also those acted upon button-based devices, such as laptops, PDAs, or mobile phones.

Around-Device Interactions (ADI), on the other hand, refer to those made on the physical space surrounding the interactive surface (next to it, above, etc.). In co-located multiuser scenarios, on-device interactions such as touching a screen could cause interference problems caused by several users trying to touch the same region at the same time, and occlusion issues if the interactive device is small. ADIs allow exploiting the 3D space around the display, thereby enabling richer interactions such as tridimensional manipulations (Hilliges et al., 2009; Kratz et al., 2012) or avoiding the issues stated above (Hasan et al., 2013; Jones et al., 2012). One possible drawback of ADIs is that they are probably less precise than on-device interactions, although, to our knowledge, this has not yet been demonstrated. However, an MDE could benefit from the combination of both, on- and around-device, media to enrich user experience. It is important to note that, according to our definition above, direct interactions do not need to occur on the device itself but to be contained within its boundaries. Therefore, it is possible to have ADIs that are indirect, such as the traditional mouse-based ADIs (Benko and Feiner, 2005) or the one in Blinkenlights (Chaos Computer Club, 2001), but also to have direct ADIs like MarkAirs (Garcia-Sanjuan et al., 2015c, 2016a), which manipulate the objects of the tablet they have immediately underneath.

Interaction Instruments

Depending on what instrument is used to perform the interaction, the interaction can be *body-based*, *surface-based* or *tangible*. In body-based interactions we can differentiate between *hand-based* and *foot-based*. The former considers the users' hands, or particularly, their fingers, as the instrument to perform the interaction with. These, including touch and mid-air gestures, are the most popular means of interaction with the available surfaces such as tablets, and they have been shown adequate for all kinds of users, from kindergartners (Nacher et al., 2014b, 2015b) to the elderly (Loureiro and Rodrigues, 2011). Foot-based interactions, on the other hand, have been less explored and rely on using one's own feet to interact, normally, with a surface on the floor (Law et al., 2009; Leo and Tan, 2010; Velloso et al., 2015). Surface-based interactions are based on manipulating the screen's device to trigger a reaction on itself, for example, by making a gesture with it (Merrill et al., 2007) or bumping two devices together (Hinckley, 2003; Schmidt et al., 2012). Tangible interactions involve a physical object which trigger a response on the MDE, and we differentiate between interaction tangible-specific and tangible-generic. The former relies on specific-purpose peripherals such as external keyboards (Mano et al., 1981), mice (Nacenta et al., 2006), digital pens (Hinckley et al., 2004), the keyboards themselves and the buttons of laptops and mobile phones (Fails et al., 2010), foot platforms (Sangsuriyachot et al., 2011), or using one surface simply as a remote controller of another (Gjerlufsen et al., 2011; Hunter et al., 2010). Tangible-generic interactions consider physical objects of general purpose (Kohtake et al., 2007) that can additionally be bound to digital elements or trigger specific actions (Catala et al., 2012b; Konomi et al., 1999). Coutaz et al. (2003) refer to this last type of interactions as generic "interaction resources." In general, tangible interactions, a.k.a., Tangible User Interfaces (Ishii and Ullmer, 1997; Shaer and Hornecker, 2010), offer spatial mapping, input/output unification, and the support of trial-and-error actions that can exploit innate spatial and tactile abilities, and so represent very powerful instruments for use in MDEs.

Input Continuity

Input continuity refers to how long an action lasts for the system to consider it a discrete input. The continuity can be *punctual* if the input is associated to a discrete contact (Hinckley, 2003; Hunter et al., 2010; Mandryk et al., 2001), or *gestural* if it involves a continuous gesture (Garcia-Sanjuan et al., 2015c; Hinckley et al., 2004; Ohta and Tanaka, 2012). We do not consider drag operations as gestural inputs since they involve a continuous action to trigger a continuous response, or, in other words, they can be seen as multiple discrete punctual inputs. Instead, a gestural input would be, for instance, drawing a “P” on the screen to start playing a song.

Although punctual interactions may be simpler to perform than gestural, making gestures can be quicker in some situations serving as a shortcut to a given UI element instead of having to navigate through the interface looking for it in nested collections, or they can enable richer experiences like fun (Morris et al., 2006), which could be useful in some application domains.

2.5 Additional Considerations related to Context

Addressing the technical dimensions explored above is crucial for building an MDE since they provide an answer to what can be done with the system, and how it can be done. Yet, information about who is going to use the platform, where, and what for has often been disregarded in previous studies that offer a taxonomy for these environments. In our opinion, a great deal of attention should be paid to these considerations of the context of the environment in order to ensure building meaningful experiences which lead to the system being well accepted. In this section we discuss three dimensions that respond to the previous three questions about the context surrounding an MDE: user information (who?), location (where?), and purpose (what for?).

2.5.1 User Information

We identify five issues related to user information that should be taken into account when designing MDEs: number of users, their age, their physical and mental conditions, and sociocultural practices. However, there is a wide spectrum of other user conditions that might affect the design of MDEs. Terrenghi et al. (2009) provide some insights in this respect and explore how the number of users and the social interactions between them have an impact on some technical dimensions of the MDE such as size. In particular, the authors state that small environments are more suitable for small groups of users because information is better managed, whereas bigger ecosystems, possibly deployed in public spaces, can allocate more users and foster productivity and social activity. Users’ age is also important to consider, for instance, MDEs built for small children or elderly people, who might have trouble working with small spaces or performing fine-grained interactions, could benefit from big and irregular topologies as well as coarse on-device and around-device interactions. Also, they could benefit from intuitive instruments of interaction such as their own hands, body, and generic tangibles they are familiar with. Another important consideration is the users' physical condition, since the system should be accessible to people with certain impairments. For example, when designing for people with reduced mobility one might not want to design perch- or chain-sized environments that would require users moving from their seat, and fixed topologies as well as static couplings might be preferred. Their mental conditions should also be taken into account because different cognitive issues may affect the perception of contents and interaction. As an example, direct, on-device, and body-based interactions might be preferred for people with certain cognitive impairments. Also, in order to avoid awkward situations, as pointed out by Hinckley et al. (2004); Terrenghi et al. (2009), any different cultural or social practices among the different users should also be considered, since they could affect the contents displayed on the screens or the interactions that should be supported. For example, it could affect privacy considerations and also interaction medium and instruments, because a user might not feel comfortable performing around-device gestures or certain foot-based interactions that resembled dancing in the presence of strangers.

2.5.2 Location

Since all MDEs must be deployed in a physical space, the physical constraints it presents should also be taken into consideration, for example, the dimensions of the room, connectivity quality, the presence or absence of seating, luminosity, etc. The size of the room will generally restrict the size of the ecosystem, and probably its mobility and scalability. Connectivity is very important for MDEs since different displays have to be in the same network in order to exchange information. The presence of low quality connectivity, or even the absence of it, could lead designers to adopt implicit coupling mechanisms, or fixed topologies in which the different devices relied on wired networks. The absence of seating might cause some discomfort in certain users, and perhaps a good solution would be opting by dynamic couplings where the users might move around and not be standing all the time in the same position. Similarly, on-device interactions on table-like surfaces would cause standing users to bend over very often, therefore, designers should consider using around-devices instead. Luminosity issues are also worth considering since they could affect the proper viewing of the contents displayed. In sum, the location where the environment is going to be deployed affects the design of MDEs. We have provided a few examples of the restrictions it can present, although the huge number of potential issues makes it impractical to enumerate them all.

2.5.3 Purpose

Finally, designers should keep in mind the final purpose of the ecosystem and let it drive the design of all the dimensions specified above. The different environments can have many application domains, e.g., gaming, education, entertainment, business, etc. and each one of them can be targeted to fulfil a myriad of specific purposes. For instance, in a game designed for young children, where physical exercise is encouraged, the environment should be at least perch-sized, and/or should have dynamic mutability to allow users to freely move around the environment. On the other hand, if the environment is aimed at hosting a business meeting, it should probably be yard-sized and allow different privacy policies to be defined. As another example, total interaction availability would probably be useful in gaming, but perhaps in a classroom the teacher might want to use partial interaction availability in which they interact with a display and the students can just watch on their own what the teacher is doing.

2.6 Conclusions

This paper reviews existing multi-display environments and classifies them into a common framework with the purpose of guiding future designers in identifying the dimensions of an MDE explored so far and how they could be successfully achieved. Our taxonomy builds upon previous ones that focus on specific parts or partial definitions of these ecosystems and provides a more general and wider conception. In particular, it works around three main axes: the physical topology of the environment, how the different surfaces that comprise it can be coupled and work together, and the different ways of interacting with the environment. Besides these technical features, we provide additional considerations on the context surrounding the MDE, namely, who is going to interact with it, where, and for what purpose. We argue for giving as much importance to technical dimensions as to these other considerations, because having the latter drive the design of the former will lead to meaningful technological environments suited to the users and therefore increase their chances of success.

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Part II

MarkAirs: A Mid-Air Approach

Chapter 3

Around-Device Interactions: A Usability Study of Frame Markers in Acquisition Tasks

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Abstract

Digital tabletops present numerous benefits in face-to-face collaboration environments. However, their integration in real settings is complicated by cost and fixed location. In this respect, building table-like environments using several handheld devices such as tablets or smartphones provides a promising alternative but is limited to touch interaction only. We propose instead another kind of "around-device" interaction (ADI) technique using the built-in front camera of these devices and fiducial frame markers, which presents advantages including better awareness and less interference. This paper contributes a first step in exploring the potential of this interaction technique by conducting a usability test comparing several ergonomic factors that may have an effect on the very first operation of the interaction: the acquisition of the marker.

3.1 Introduction

Digital tabletops have been shown to be very suitable tools for use in collaborative environments (Gutwin et al., 2006; Hornecker et al., 2008). Their form factor improves workspace awareness (Hornecker et al., 2008), and their multi-touch capabilities allow simultaneous interaction. Together, this increases parallelism, allows more democratized access, and leads to an increased collaborative performance, which produces better results (Hornecker et al., 2008; Rick et al., 2011). Nevertheless, it is rare to see tabletops embedded in real settings. This is due to a number of disadvantages: their high cost; their limited workspace dimensions, which can only accommodate a certain number of participants; and the fact that their form factor complicates mobility in a way that, nowadays, if a digital tabletop is available, it is fixed to a single location and users are forced to move to a specific place if they want to engage in a collaborative activity around it. Ideally, it would be desirable for users to be able to form groups in an improvised way, in virtually any place, and of any size, using the devices they have with them to dynamically create a tabletop-like collaborative space. This allows us to take advantage of the benefits of tabletops in terms of awareness and parallel interaction, but using a different approach to tabletop working based on handheld devices. Devices such as smartphones or tablets are becoming increasingly popular and will be in common use in the near future. The portability of these devices implies that it could be possible to build multi-display environments (MDE) to support co-located collaborative activities on a table-like setting by coordinating interaction across several devices put together on the same table. However, this scenario raises a new challenge. As Gutwin et al. (2006) found out, in highly integrated collaborative scenarios, users often have the need to acquire elements that are out of reach. Therefore, since interaction with handhelds is usually carried out by touch contact, in a situation where several users are gathered around the same table, interference problems may arise related to simultaneous touch actions from different users on the same surface. The immediate solution comes by asking others to hand over the elements. However, this could interfere with the task another user is currently carrying out. Another possible solution is Around-Device Interactions (or ADIs, Kratz and Rohs, 2009), where a user could interact with an out-of-reach tablet which is at the same time being manipulated via touch by another user, and without interfering with the latter's actions. We explore the potential of fiducial frame markers as an enabler of ADI.

Our end future goal is to design MDE collaborative environments around a table like the one shown in Figure 3.1, where users bring their own devices and where they may use cards or tangible elements with attached fiducial markers to share objects (e.g., documents, game elements) or trigger reactive behaviors in a target surface on the table. The built-in camera in each device is used for the marker detection; therefore no additional hardware infrastructure is required. In this kind of setting, several interactive surfaces can be placed on a table at different distances, rotations, etc. Thus, the entry point at which users approach each surface can dramatically change, and so can the conditions surrounding the

Figure 3.1: Hypothetical collaborative scenario with ADI using fiducial markers.

interaction itself. As such, before designing any complex ADI for these settings, the fundamental issue that must be addressed is the acquisition of the marker (Tuddenham et al., 2010), i.e., the initial step at which the fiducial marker is placed in the camera's field of view for it to be detected, and evaluating how usable this is under different conditions. The main aim of this paper then is to present an ADI technique that uses fiducial markers and to obtain the ground knowledge that will enable us to design a table-based MDE that uses it effectively. Specifically, we evaluate the usability of the acquisition phase of the proposed ADI through an in-lab study, focusing on the ergonomic conditions that are perceived as facilitators of this interaction.

3.2 Related Works

There are a number of different ADI techniques with varying degrees of flexibility and hardware complexity. For example, Hasan et al. (2013) present AD-Binning, an ADI used to extend the workspace given by the small screen of a smartphone by including their surroundings. Users then interact with the smartphone by using a ring-shaped band on their fingers, and store/retrieve items to/from the extended space. Both the device and the ring are tracked by a complex hardware setup formed by eight external cameras. While this may be precise, it is not available to the common user and requires previous assembly and calibration. Avrahami et al. (2011) also explore ADI by using cameras mounted on both sides of the tablets to track distinct objects and capture interactions in the space near the device. While this approach allows mobility and the possibility of forming groups of users virtually anywhere in an improvised way, it still requires a careful installation of external hardware. A simpler approach is by Kratz and Rohs (2009), who attach external IR sensors on a smartphone screen, and allow ADI using hands. Their main purpose is to reduce the occlusion produced by touch contacts, which is a form of interference. Other works reduce the hardware complexity even further by making use of the integrated sensors in the tablets. Ketabdar et al. (2010), for instance, exploit the magnetic (compass) sensor of the device, and interact around it using magnets. Unlike optical approaches, this solution is more robust to occlusion. They also can shape the magnets in different forms, though the system is not capable of differentiating between different magnets since they do not have an encoded ID. This prevents its use in applications with multiple collocated users.

Although the previous examples enable ADI by augmenting tablets with external sensors, they are designed to be used by a single user and on one device. Probably for this reason most of them (Avrahami et al., 2011; Ketabdar et al., 2010; Kratz and Rohs, 2009) require the interactions to take place close to the device. In a table-based MDE, this restriction could require that users lean over the table or even move towards the target device, which could be cumbersome and cause interference with interaction on the other devices.

Finally, Nacenta et al. (2007) compare several interaction techniques, including ADI, in tabletop groupware in terms of how they enhance coordination. They include aspects like lack of interference, ease of transference of elements, and easy access to out-of-reach zones as important factors. Our work complements this previous work by considering other forms of interaction based on fiducial markers and studies the ergonomic, visual feedback, and marker size factors.

3.3 User Evaluation

In its simplest form, the proposed interaction consists of taking a card with the marker and bringing it close to a selected tablet for recognition. To study the usability of this, we identified seven ergonomic factors that may have an effect on this initial interaction phase: the *user posture* (sitting vs. standing), the *active hand* (non-dominant vs. dominant), the *marker size* (small vs. big, as shown in Figure 3.2), the *tablet position* with respect to the users (whether it is at their non-dominant vs. dominant side), the *tablet distance* to the users (near vs. far, depending on whether it is within arm's reach or not), the presence of a *visual feedback* on the tablet that allows the users to see what the camera sees (missing vs. present), and the users' *gender* (male vs. female). In presenting the results (see Figure 3.3), the first condition listed is represented as "level –" and the second as "level +," e.g., sitting is the "–" level and standing is the "+" level for the *user posture* factor.

3.3.1 Apparatus

The experiment was conducted with a 120×80cm table 75cm high in an environment with ambient light intensity ∼150-200lx, and without any direct light source above the table. The surface's table was visually divided across both horizontal and vertical axes, resulting in four identical rectangular sectors to account for near/far tablet distances and non-dominant/dominant tablet positions. When required, the users sat on a chair 47cm high. The marker detection application

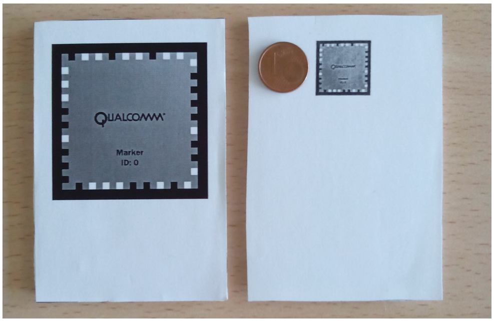

Figure 3.2: Cards with the fiducial frame markers used in the experiment.

was running on a Samsung Galaxy Note 10.1 tablet using the computer vision algorithms provided by Vuforia™ for Android devices. Visual feedback about the position of the marker with respect to the camera was given by video on the display. The size of this video region was 1/9 the screen size, and it was located in the lower-left corner. The size of the big and small markers was 50×50mm and 17×17mm respectively, and both were printed on a cardboard card of dimensions 63×91mm and situated near the top (see Figure 3.2).

3.3.2 Participants

Thirty-two volunteers, 16 male and 16 female, participated in this study. Ages ranged from 24 to 48 ($M = 32.28$, $SD = 6.3$). The average height of males was 180.88cm ($SD = 7.27$), and females' was 167.38cm ($SD = 7.14$). Four of them were left-handed and the rest, right-handed.

3.3.3 Design

Since the number of factors considered is high and it would be impractical to have each user perform every combination of their levels, the experiment follows a mixed fractional factorial design 2_{IV}^{7-3}, for which only 16 different treatments are needed; and, since gender is a between-subjects factor, each user only had to conduct 8 treatments. A total of 1536 interactions were performed across factors and treatments. To avoid order and carryover effects during the performance of the 8 treatments by a given subject, the order in which the treatments were presented follows an 8×8 balanced Latin Squares design for each gender.

3.3.4 Procedure

Firstly, the users were given some time to train with the system in order to minimize posterior learning effects. During this training, they practiced the experimental task which consisted of taking the card with the marker and bringing it

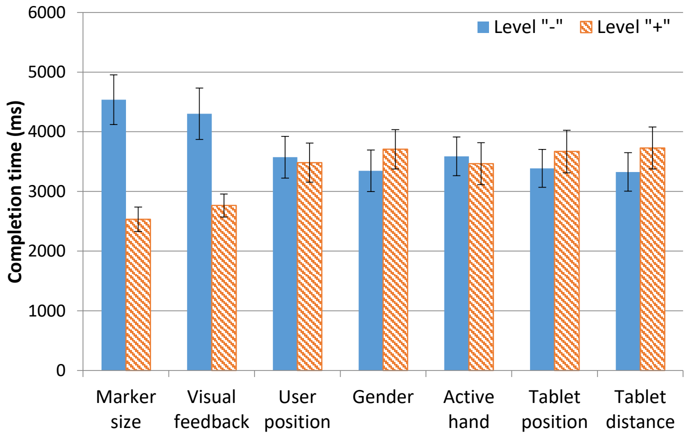

Figure 3.3: Mean completion times (in milliseconds) for each considered factor.

closer to the tablet's camera for it to be recognized. Once they felt familiar with the interaction, the proper experiment began, where one user at a time had to repeat the previous interaction but following the instructions given by the different factor treatments (i.e., being seated or standing, holding the marker with their dominant or non-dominant hand, having the tablet near or far, etc.). Each treatment was repeated six times, and subjects were encouraged to perform this interaction as quickly as possible. For each treatment, the average elapsed time to the detection of the marker was measured, and the users filled a NASA-RTLX questionnaire (Byers et al., 1989) to assess subjective task load. Once all treatments were complete, a System Usability Scale (SUS) questionnaire (Brooke, 1996) was administered to evaluate the usability of the technique. Users were also asked about their experiences in a short post-task interview.

3.3.5 Results

Regarding quantitative differences, Figure 3.3 depicts the mean completion times by each factor. A repeated measures ANOVA (with an $\alpha = 0.05$) revealed only two factors having a significant effect on the response variable: the marker size ($F_{1,243} = 19.514$, $p < 0.001$) and the visual feedback ($F_{1,243} = 11.555$, $p = 0.001$). No double or triple interactions were found significant. The shorter times correspond to performing the interaction with the big marker and having visual feedback, respectively.

NASA-RTLX scores for workload were analyzed using Friedman's χ^2 tests for ranks ($df = 1$). Subjects reported relatively low levels of mental, physical, and temporal demand for all conditions, as well as low levels of effort and frustration. All of the above were rated between 20 and 30 approx., with 0 meaning "very low," and 100 "very high." However, some aspects show significant differences between the levels of factors in some conditions. Participants reported a significant lower degree of workload in general using the big marker and having the tablet near. Concretely, these two conditions received significantly ($p < 0.05$) lower scores of mental/temporal demand, effort, and frustration. Subjects also made less effort ($p = 0.034$) when the visual feedback via video was shown. No significant differences were found between postures, but subjects perceived using their dominant hand as less physical ($p = 0.009$) and time demanding ($p = 0.009$). As for differences between gender, women reported significantly ($p < 0.05$) lower levels of workload in general than men. Concretely, they reported lower levels of mental demand, effort, and frustration, and they showed more confidence regarding performance than men, whose scores were more neutral.

The perceived general usability of the ADI technique was studied via a SUS questionnaire. The analysis using Mann-Whitney U tests revealed no significant differences between genders ($U = 90.5$, $p = 0.156$). The SUS total score (calculated as it is explained by Brooke (1996)) is, on average, 73.13 ($SD = 11.46$) for men, and 75.63 ($SD = 20.18$) for women, which, according to Sauro's guidelines (2011) is above average (68). In Sauro's letter-grade system (from A+ to F), the overall usability of our technique would receive a B.

3.3.6 Discussion

The results show that the proposed interaction technique is usable in general (obtaining a B grade from the SUS questionnaires). This was also confirmed by some subjects' comments regarding the good performance of the system and their suspicions about whether this was a real working prototype.

Further, the quantitative analysis has not found any statistically significant effects related to the posture of the users (sitting vs. standing), the side at which the device is located (dominant vs. non-dominant) and its distance from the user (near vs. far). This proves that the technique is usable under a wide spectrum of ergonomic situations. Moreover, the fact that subjects reported low levels of mental, physical, and temporal demand for all conditions means that the analyzed interaction is intuitive and potentially applicable to more demanding scenarios with subjects having cognitive or motor disabilities. However, the analysis of the qualitative results shows some implications for future applications using the interaction technique considered in this work. Several participants reported having difficulties with the visibility of the video feedback when they were seated and the tablet was not located within arm's reach. This issue disappeared when they were standing up. Hence, this suggests that activities designed for situations where the users are seated should either keep the devices within arm's reach for all participants or avoid video feedback.

Subjects also reported using their dominant hand was less physically and time demanding. However, this did not have a significant impact on the time to perform the gesture and some participants even commented they preferred to use one hand or the other depending on which side the tablet was on. This observation provides initial clues about the feasible use of both hands to allow bimanual aerial interactions in the design of future ADI systems. Visual feedback and marker size had a greater impact on the interaction. The small marker was harder to recognize by the application, and the users needed to put it very close to the camera, which made them "lean too much" on the table when the tablet was distant. In a real application, this could cause interference with others' actions and lead to much more frustration. Therefore, the results suggest that big markers are more suited for this sort of interaction. They can be attached to cards and, because the proper marker is a frame, they can be filled with application-specific content. Taking advantage of markers' IDs, a potential use for these cards could be using them as information containers and also for the transfer of elements/documents in a co-located group, which many subjects of our experiment showed great excitement about. According to Nacenta et al. (2007), an interaction like this one, using the card as an information container, presents intrinsic benefits in terms of awareness since the system does not need to present any action points to the user (e.g., via a cursor), and because any user can easily identify which colleague performed a given gesture with the card because of the visibility of such actions. On the other hand, having visual feedback in a small region of the screen was perceived as a very useful feature for allowing users to adjust and correct their actions. Similar benefits from visual feedback are reported by Nacenta et al. (2007). Nevertheless, some subjects pointed out that it might not be convenient to integrate this feature, since it would reduce the display work area.

3.4 Limitations and Future Work

It is important to note that, as Nacenta et al. (2007) remark, the choice of a given interaction technique affects coordination, preference, and performance. Hence, the results reported in this paper are only conclusive for this particular interaction. There are also several limitations to our work. Firstly, the experiments were performed with the same tablet brand and model, and the resolution of the camera could have an effect on the recognition. Secondly, the study only refers to the initial acquisition phase of the interaction. However, analyzing the feasibility of this initial phase and obtaining first user impressions is a necessary step forward before designing and considering more complex scenarios based on ADI. Regarding this, the results obtained provide useful information for future designers of ADI-based environments using frame markers. As a next step, we plan to perform a full study of different types of ADI marker-based manipulations to obtain a full set of feasible interactions with this technique. Another limitation is that the controlled interaction was performed in isolation by a single user and, therefore, no interference issues that could happen in a collaborative scenario were evaluated. This is certainly an interesting area of future research to evaluate the full potential of the proposed technology to support MDE collaboration.

Despite these limitations, the relatively good usability results obtained encourage us to delve into the ADI proposed in this paper, and conduct further experiments that test its suitability in actual collaborative environments. Regarding future uses, we consider this interaction to be promising in meeting environments where users could easily exchange documents attached to marker cards. Another potential application domain is gaming, where, for instance, the tablets could be used in consonance with a physical gaming board offering digital augmentation, whereas the cards could encode abilities or objects to be transferred to the other participants. Physical games could also be implemented in which participants would exercise by moving around a big table with their cards obtaining and depositing items from the tablets scattered on it. This ADI could also be interesting in rehabilitation tasks for people with acquired brain injuries. In this case, markers could be attached to tangible elements that represent objects in real life and the patients should have to reach the tablet (among several others) that shows some digital content related to the element they are holding.

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Chapter 4

MarkAirs: Around-Device Interactions with Tablets Using Fiducial Markers—An Evaluation of Precision Tasks

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Abstract

This paper evaluates MarkAirs, an interaction technique that uses fiducial markers to perform mid-air interactions. MarkAirs offers several advantages: the proposed technique does not require any tracking external hardware other than the

Figure 4.1: Interaction with MarkAirs to control the position of an element. On the left, the fiducial marker used.

front camera of a mobile device; it is robust even when the markers are partially occluded; and it enables precise 2D manipulations (translation, rotation and scaling). An evaluation study points to the feasibility and precision of the proposed technique and the perceived usability and subjective workload impressions of the participants.

4.1 Introduction

Handheld devices are becoming widespread and offer several advantages with respect to tabletops in terms of cost, scalability, and mobility to build collaboration spaces (Garcia-Sanjuan et al., 2015a; Rädle et al., 2014). In these scenarios, mid-air or Around-Device Interactions (ADIs) could be used to enable manipulations in the available 3D space above the surfaces. However, when ADIs have been implemented in the past they have required pre-installed specialized hardware that limited the choice of where these interactions could take place, have not been accurate enough to perform high precision manipulations of objects on the devices, or have relied on hand and finger gestures which do not allow the identification of the users.

In this work, we present MarkAirs (see Figure 4.1), an interaction technique that makes use of the built-in front camera of handheld devices and fiducial markers to enable precise ADIs. We do not only show that interactions above handhelds are realizable without any external specialized hardware, but also evaluate the precision of basic 2D manipulations (translations, rotations, and scaling) on digital objects and the perceived subjective usability and workload of the proposed technique.

4.2 Related Works

Previous works have explored ADIs with tabletops. These exploit the space above the surface either to explore 3D virtual spaces (e.g., Spindler et al., 2009) or to reach and manipulate distant elements (e.g., Banerjee et al., 2011). These high-precision tasks, however, often rely on complex hardware settings composed of several external cameras, projectors, or gloves with reflective markers like the ones used in motion capture (e.g., Marquardt et al., 2011).

Other approaches rely on embedded cameras that are installed within tabletops to recognize aerial interactions. Hilliges et al. (2009), for example, use an "enhanced" tabletop and make use of hands to perform gestures in the air to manipulate 3D digital objects rendered on a tabletop. However, even though hands enable natural interactions, they do not allow the identification of the user who makes them. To solve this problem, Gallardo and Jordà (2013) propose the use of fiducial markers for such interactions. However, their approach requires expensive specially designed hardware to control the degree of transparency of the surface, so that image projection and gesture detection are interleaved. Moreover, their markers cannot be occluded for the system to work properly.

Several works have explored ADIs for handheld devices using external cameras or depth sensors with the purpose of performing 3D rotations using hand gestures around the handheld (e.g., Kratz et al., 2012), reducing the occlusion produced by touch contacts on the screen (e.g., Jones et al., 2012), or mitigating the cluttering of the surface by storing/retrieving digital elements to/from the space around the device (e.g., Hasan et al., 2013). These approaches allow performing manipulations with a certain precision but, again, require careful installation of external hardware. Others reduce the hardware complexity by making use of the built-in sensors in the tablets. Ketabdar et al. (2010), for instance, exploit the magnetic (compass) sensor of the device and enable in-air interactions using magnets. Unlike optical approaches, this solution is more robust to occlusion, but it is less precise and the system is not capable of differentiating between different magnets since they do not have an encoded ID. In contrast, others rely on the built-in camera of the devices to detect hand gestures (e.g., Song et al., 2014) or fiducial markers (e.g., Garcia-Sanjuan et al., 2015a). Whereas the former avoids any additional equipment, the use of markers enables the identification of the user as well as detecting as many actions as markers available, which are considerably higher than the gestures that can be achieved with hands only. However, the use of frame markers by Garcia-Sanjuan et al. (2015a) is not robust to the occlusion of the marker and the precision of the technique to perform fine-grained manipulations is not evaluated.

4.3 Interacting with MarkAirs

As explained by Garcia-Sanjuan et al. (2015c), MarkAirs is an ADI involving fiducial markers that are recognized by a tablet's front camera (see Figure 4.1

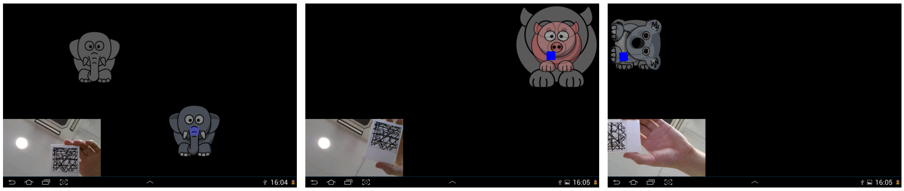

Figure 4.2: Manipulations evaluated: translation (left), rotation (center), and scaling (right).

and Figure 4.2). These markers can be attached to physical cards or objects or even displayed on other digital devices, and consist of arbitrary drawings that are tracked by Vuforia™'s natural feature tracking algorithms. They present several advantages with respect to other more classical kind of markers (e.g., the ones used by Gallardo and Jordà, 2013; Garcia-Sanjuan et al., 2015a): a) they can be tracked even if they are partially occluded (see the bottom-left corner of the tablet in Figure 4.1, which shows the image captured by the device's camera); b) one can have a virtually infinite number of markers; and c) a marker can be a meaningful photograph, which can be related to the digital information content that is associated with the card (e.g., if we want a card to contain a game character, the marker can be a picture of the character itself).

In this work, the marker's 3D position and orientation are mapped to 2D manipulations as follows: translation (marker's position in the XY axes), scaling up/down (marker's position in the Z axis), and rotation (marker's yaw angle).

4.4 Evaluation

The following reports on an evaluation study of the use and usability of MarkAirs as a potential ADI technique. This study had three goals: First, to determine the level of precision that can be achieved both in the termination phase of the proposed 2D manipulations (when reaching a final desired position/orientation/size), and in the execution phase (when translating/rotating/scaling at a given pace or following a specific trajectory). Second, to assess whether there are differences in the precision achieved when these manipulations are performed in isolation (first translation, then rotation, and finally scaling) and when all three are performed conjointly in the same task. And, finally, to obtain insights into the perceived subjective usability and workload of the proposed interaction.

4.4.1 Participants and Apparatus

Twenty-four volunteers participated in this study, fifteen of whom were males, with ages ranging from 14 to 60 ($M = 34.54$, $SD = 12.30$). The experiment was conducted with a 10.1" Android tablet having a resolution of 1280×800 pixels, and running Vuforia™'s computer vision algorithms. A 5×5cm marker was attached to a 6×9cm piece of cardboard, as depicted in Figure 4.1 (left).

4.4.2 Tasks

Eight different tasks were performed (see supplementary video[1]), three to evaluate the precision of each 2D manipulation in the termination phase, three to evaluate the precision in the execution phase, and two to evaluate the precision of all three manipulations being performed conjointly in the termination and the execution phase, respectively. In all tasks there is a target 2D object (O_T) to be manipulated by means of ADIs and a reference 2D object (O_R) whose random position, orientation or size must be reached (see Figure 4.2).

The termination-precision tasks are carried out in three steps. First is an *acquisition* step in which the participant must use the marker to control a small squared cursor on the screen and acquire O_T. Once acquired, the task moves on to a *manipulation* step, when the corresponding manipulation must be performed to make O_T reach O_R's position, orientation, and/or size (depending on each task). Once the system determines that O_T and O_R match within a certain error margin, i.e., at least 90% overlap (position/size) and/or their respective orientations differ less than 10º, the task moves on to a *precision measuring* step. In this step the participant must maintain O_T as close as possible to O_R (which remains static) for 5 seconds while the system measures precision (which will be described below).

The execution-precision tasks are on the other hand conducted in two steps. First is an *acquisition* step, as described above. Second, once O_T is acquired, there is a *manipulation* step in which O_R continuously and dynamically changes its position, orientation, and/or size (depending on the task) for 40 seconds. The participant must continuously perform the manipulation to maintain O_T as close as possible to O_R while the system measures precision.

4.4.3 Procedure and Experimental Design

The participants stand in front of the tablet placed on a table. The first stage of the experiment is to explain the interactions to the users and give them some time to train in order to minimize learning effects. Once they feel familiar with the interaction, the experiment begins. Each user performs the three manipulations (translation, rotation, and scaling) with two different precision measurement situations or phases (termination and execution), first each manipulation separately, and then combined. In order to avoid order and carryover effects, the isolated manipulations are presented following a 3×3 balanced Latin Squares design. For each manipulation, the termination-precision task is presented first, followed by the execution-precision one.

The manipulation error during the *precision measuring* step is measured for each task as follows: the distance in pixels between the centers of O_T and O_R

[1] `https://www.dropbox.com/s/0ewgy3xw8ri1u1f/MarkAirs.avi`

Table 4.1: Average (and standard deviation) errors for each manipulation performed separately (in columns) and phase (in rows).

Phase	**Translation error (px.)**	**Rotation error (deg.)**	**Scaling error (%)**
Termination phase	11.92 (4.45)	3.09 (2.84)	2.91 (1.68)
Execution phase	15.89 (5.82)	6.11 (4.49)	5.44 (3.32)

for the translation tasks, the difference between their orientation angles in degrees for rotation tasks, and the difference between their scaling factors in percentage for scaling tasks. This error is calculated as the average of a number of samples obtained continuously during the *precision measuring* step. When all three manipulations are performed conjointly, all three errors are measured. In addition, the subjective workload of each task is measured via the NASA-RTLX questionnaire (Byers et al., 1989). Finally, a SUS questionnaire is administered post-tasks to evaluate the overall usability of the technique.

4.4.4 Results

Precision Errors

For each 2D manipulation executed separately, the users performed a total of 72 (24 users $\times$ 3 manipulations) interactions in the termination-precision task and 72 in the execution-precision task, so that each 2D manipulation was performed 144 times. Table 4.1 shows the average (and standard deviation) error measures for each type of manipulation and phase. Additionally, a repeated measures ANOVA ($\alpha = 0.05$) showed a significant effect of the phase on the precision error for translation manipulations ($F_{1,71} = 51.029$, $p < 0.001$), rotations ($F_{1,71} = 23.055$, $p < 0.001$), and scaling ($F_{1,70} = 37.453$, $p < 0.001$), with the termination phase outperforming the execution one in terms of precision.

Table 4.2 shows the average (and standard deviation) errors for each manipulation in the task where all three are performed conjointly, also both in the termination and execution phases. A repeated measures ANOVA ($\alpha = 0.05$) also showed a significant effect of the phase on the precision error for translation manipulations ($F_{1,71} = 155.358$, $p < 0.001$), rotations ($F_{1,71} = 83.857$, $p < 0.001$), and scaling ($F_{1,71} = 108.429$, $p < 0.001$), with the termination phase outperforming the execution one.

Additionally, pairwise within-subject t-tests ($\alpha = 0.05$) were conducted to assess whether the errors obtained performing each manipulation individually differed from when all three were combined in the same task, showing only significant differences for the translation in the execution phase ($p < 0.001$), the rotation in the termination phase ($p = 0.036$), and the scaling in the execution phase ($p < 0.001$).

Table 4.2: Average (and standard deviation) errors for each manipulation performed conjointly with the other two in the same task (in columns) and phase (in rows).

Phase	Translation error (px.)	Rotation error (deg.)	Scaling error (%)
Termination phase	11.93 (5.53)	2.05 (2.92)	3.51 (2.24)
Execution phase	31.11 (12.75)	6.94 (3.71)	9.94 (5.12)

Qualitative Measures

NASA-RTLX scores for workload assessment were analyzed for the different manipulations both individually and all combined. In general, the users reported relatively low workload, rating all dimensions on average between 13.13 and 26.88 (0 being "very low" and 100 "very high") when each manipulation was performed individually. When performed conjointly, the workload slightly increased across all dimensions on average (rating between 27.92 and 37.40). Besides, differences were found between some of the manipulations; pairwise comparisons using Wilcoxon signed-rank tests with a Bonferroni adjustment ($\alpha = \frac{0.05}{C(4,2)} = \frac{0.05}{6} = 0.008$) revealed that scaling manipulations were considered significantly less time-demanding than translations ($p = 0.001$), and also received significantly better performance scores ($p = 0.003$), and lower values for effort ($p = 0.001$) and frustration ($p = 0.003$). Not surprisingly, performing all three manipulations at once received worse workload assessments overall, except in two cases: no significant differences were found between only translating and performing all three manipulations in terms of performance ($p = 0.021$) and frustration ($p = 0.124$).

The phase in which the manipulation occurred (termination vs. execution) was also analyzed using Friedman's χ^2 tests for ranks ($df = 1$, $\alpha = 0.05$), and the results showed the participants perceiving manipulating at the termination phase with a static object less demanding in terms of workload in all NASA-RTLX dimensions ($p < 0.001$).

The general usability of MarkAirs, assessed via a SUS questionnaire, shows a total average score (calculated as in Brooke, 1996) of 83.44 ($SD = 13.31$), which, according to Sauro (2011) is above average (68). In his letter-grade system (from A+ to F), the overall usability of MarkAirs would receive an A.

4.4.5 Discussion

In terms of the precision of the proposed aerial interactions in the termination phase, the implemented technique offers acceptable levels for all three manipulations (translation, rotation and scaling) and it allows users to perform fine-grained interactions with average errors of 11.92 pixels, 3.09º, and 2.91%, respectively when only one manipulation is being carried out at a time. When users have to perform all three manipulations conjointly to move, rotate, and resize an element, the translation and scaling average errors increase slightly but insignificantly, and the rotation error in this case even decreases significantly to 2.05º (probably due to a learning effect since the task combining all three manipulations was performed last).

It is also interesting to note that the precision of the proposed interactions worsens in the execution phase, when the users are forced to adapt their behavior to a given dynamic trajectory, rotation, or size of the reference object. Moreover, when all manipulations are performed together, the translation and scaling operations are significantly less precise than when they are performed individually (average errors in the worst case of 31.11 pixels, 6.94º, and 9.94%). This means that the proposed technique, although supporting these additional dynamic execution requirements, would not be adequate for very high-precision 2D manipulations.

In terms of subjective perception, MarkAirs showed a very good SUS usability score (an A grade) and low workload levels, in general. Moreover, the scaling tasks received better subjective impressions with respect to time demands, performance, effort, and frustration, in comparison with the other two manipulations. This could be explained because scaling by means of a vertical arm movement is perceived as requiring little ergonomic effort. In addition, as it was expected, the users clearly expressed better subjective workload impressions of the tasks where the reference object was static. They found the precision requirement less demanding in the termination phase than in the execution phase.

Finally, it is also worth mentioning that, during the course of the experimental sessions, the users expressed very positive comments on the interaction technique. Specifically, they referred to it as being "very fluid," "relaxing," "fun," "entertaining," and "astonishing." Indeed, it was found to cause amusement, and even in the more challenging execution-precision tasks, the subjects expressed positive reactions when the reference object changed its position/rotation/size dynamically.

4.5 Conclusions and Future Work

This paper presented MarkAirs, an interaction technique that uses the built-in front camera of a tablet/smartphone and fiducial markers to perform translation, rotation and scaling ADIs. The precision of the proposed technique was evaluated in both the execution and termination phases. The results show that good precision levels can be achieved in all situations. The analysis of the participants' responses to SUS and NASA-RTLX questionnaires reveals that they consider it highly usable and undemanding in terms of workload. Observational data also revealed that MarkAirs was an engaging and entertaining experience for first-time users. In future work, we will use the 6-DOF information obtained by the tracking algorithms to explore new ways of making translations by performing roll and pitch rotations on the marker and "project" the cursor onto the screen, thus eliminating the need for arm movements in these tasks. We consider this interaction useful for multi-user environments since it could enable richer interactions using the 3D space above the surface as well as provide identification for the users' actions and also help reduce the clutter on screen by using the cards as containers of digital elements. Another future line of research will be to study MarkAirs in a collaborative context in a multi-display environment.

Acknowledgments

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Chapter 5

Airsteroids: Re-designing the Arcade Game Using MarkAirs

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Abstract

This paper presents Airsteroids, a multi-player re-design of the classic arcade game Asteroids. The re-design makes use of handheld devices such as tablets and smartphones and of MarkAirs, an around-device interaction (ADI) with fiducial markers that reduces occlusion on the screens and interference between users' interactions.

5.1 Introduction

Handheld devices are becoming very widespread and offer several advantages with respect to tabletops in terms of cost, scalability, and mobility to build collaboration spaces (Rädle et al., 2014). Despite these advantages, in these devices interaction is usually carried out via touch contacts, which, in multi-user co-located scenarios, can be the source of multiple problems. These include interference if several users try to simultaneously touch the same display, no identification of the source of a given action, and occlusion of digital content by the participants' hands and arms, among others.

To overcome these problems, Around-Device Interactions (ADIs) could be used in these environments to enable interactions in the available 3D space above the surfaces. However, when ADIs have been implemented in the past they have either required pre-installed specialized hardware that limited the choice of where these interactions could take place, or have not been accurate enough to perform high precision manipulations of objects on the devices.

In this work, we present a re-implementation of the classic arcade game Asteroids called Airsteroids, which enables a multi-user co-located game experience. Each user brings his/her own tablet to the environment and can interact with all devices by means of ADIs using MarkAirs. MarkAirs is an interaction technique that makes use of fiducial markers tracked by the built-in front camera of these handheld devices. The user can perform several aerial gestures with the markers, which entail different behaviors to the game elements.

5.2 Related Works

Previous works have explored ADIs with tabletops. These exploit the space above the surface either to explore 3D virtual spaces (e.g., Spindler et al., 2009) or to reach and manipulate distant elements (e.g., Banerjee et al., 2011). These high-precision tasks, however, often rely on complex hardware settings composed of several external cameras, projectors, or gloves with reflective markers like the ones used in motion capture (e.g., Marquardt et al., 2011).

Other approaches rely on embedded cameras that are installed within tabletops to recognize aerial interactions. Hilliges et al. (2009), for example, use an "enhanced" tabletop and make use of hands to perform gestures in the air to manipulate 3D digital objects rendered on a tabletop. However, one of the drawbacks of their approach is that, even though hands enable natural interactions, it is not possible to identify the user who makes a given aerial interaction. To solve this problem, Gallardo and Jordà (2013) propose the use of fiducial markers for such interactions. However, their approach requires expensive specially designed hardware to control the degree of transparency of the surface, so that image projection and gesture detection are interleaved. Moreover, their markers cannot be occluded for the system to work properly.

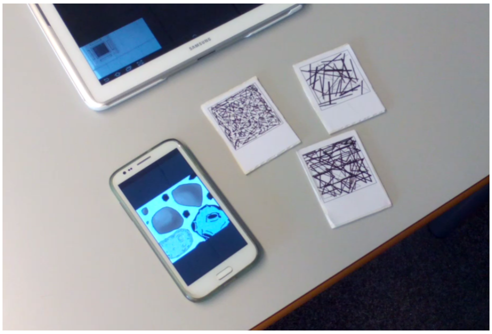

Figure 5.1: Markers used to perform interactions in the Airsteroids game.

Several works have explored ADIs for handheld devices using external cameras or depth sensors with the purpose of performing 3D rotations using hand gestures around the handheld (e.g., Kratz et al., 2012), or reducing the occlusion produced by touch contacts on the screen (e.g., Jones et al., 2012). These approaches allow manipulations to be performed with a certain precision but, again, require careful installation of external hardware. Others reduce the hardware complexity by making use of the built-in sensors in the tablets. Ketabdar et al. (2010), for instance, exploit the magnetic (compass) sensor of the device and enable in-air interactions using magnets. Unlike optical approaches, this solution is more robust to occlusion, but it is less precise and the system is not capable of differentiating between different magnets since they do not have an encoded ID.

5.3 Interaction with MarkAirs

MarkAirs is an interaction technique performed above a tablet or smartphone conducted by handling a fiducial marker which, when in the field of view of the tablet's built-in front camera, allows a computer vision software to detect the marker and track its 6-DOF pose (position and orientation) in real-time. Markers may be attached to physical cards or displayed on other digital devices allowing for multi-display ecosystems (see Figure 5.1). Unlike other works (Gallardo and Jordà, 2013), our markers consist of arbitrary drawings which are tracked by Vuforia™'s natural feature tracking algorithms. We adopted these particular markers for several reasons: First, because they can be tracked even if they are partially occluded. Second, because this system allows for a virtually infinite number of markers, since creating a new one can be achieved simply by drawing some arbitrary lines. Finally, because a marker can also be a meaningful photograph, which can be related to the digital information content that is associated with the card (e.g., if we want a card to contain a game element, the marker can be a picture of the element itself).

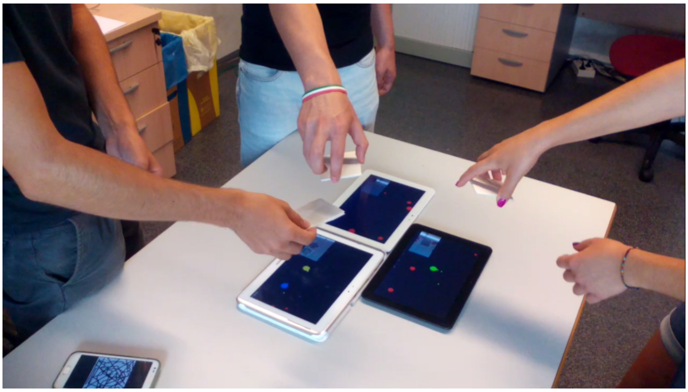

Figure 5.2: Several users playing Airsteroids.

5.4 Airsteroids

Airsteroids consists of a re-design of the classic arcade game, where a ship must destroy some asteroids coming at it before they crash. In our version, several players arrange some tablets on a surface (see Figure 5.2) and they use different markers with the MarkAirs infrastructure to handle the different game elements. There is no need to touch the screen nor pop up any contextual menus that could occlude the interface. In the proposed demo game there are three types of markers:

- *Ship controllers*: Each one of these markers represent a ship of a specific color for a given player. The marker's XY position and yaw rotation are mapped to the ship allowing it to move around the digital world and cross between surfaces. When the marker is brought down (closer to the tablet), it causes the ship to shoot.
- *Asteroids factory*: These markers allow the user to place some asteroids on any tablet by means of an up/down gesture. Once an asteroid is placed, it starts moving with a given speed and a random trajectory.
- *Property modifiers*: Modifier markers control specific properties of some game elements. For example, to modify the speed at which the asteroids move (bringing the marker up speeds up the asteroids, whereas bringing it closer to the device slows them down); others can make a spaceship indestructible during a given time span; etc.

5.5 Conclusion

In this paper we presented Airsteroids, a re-implementation of the Asteroids game using MarkAirs, an ADI technique using fiducial markers. Airsteroids is an example of a multi-player multi-device game that can enable social/collaborative behaviors. We illustrate the ways in which using aerial interactions can reduce occlusion and interference among several users' actions, which is a problem that can occur in similar scenarios where only touch interactions are available.

As future work, we intend to conduct an experiment with real players during the ITS'15 demos session in order to obtain information about the social interactions and collaborative behaviors that emerge during the course of the game. In this evaluation up to 6 co-located tablets will be used and the game will be available for download to enable ITS attendees to participate in a massive multi-player Airsteroids experience.

Acknowledgments

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Chapter 6

MarkAirs: Are Children Ready for Marker-Based Mid-Air Manipulations?

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Abstract

Interaction with handheld devices is usually limited to multi-touch input in the small display area and does not consider the space above and around the surfaces. In this paper we present and evaluate a way of exploiting this 3D space by enabling precise mid-air interactions using fiducial markers to create multi-display educational games that foster collaboration and physical mobility. Our evaluation determines that sixty children aged 6 to 12 years can effectively perform precise mid-air manipulations with these markers and reports their positive impressions of this type of interaction.

6.1 Introduction

Learning through play and serious games has been reported to be more effective than traditional instruction methods (Nacher et al., 2015a; Wouters et al., 2013).

Handheld devices such as tablets or smartphones are in almost universal use nowadays and have numerous advantages that make them suitable for their use in educational environments with children, i.e., they support the inclusion of multimedia and interactive contents, they enable direct manipulations via touch instead of indirect input via mouse, they can be shared, they are considerably cheaper than other interactive devices such as digital tabletops, etc. Albeit handhelds have been designed mainly for private use, several recent works (e.g., Garcia-Sanjuan et al., 2015c; Rädle et al., 2014) have attempted to build Multi-Display Environments (MDEs) in a way that several devices are placed near one another on a flat surface (e.g., a table) and belong to the same logical workplace. These MDEs have several benefits in terms of mobility and scalability, since devices can be moved around and users can add/remove them dynamically at will. Also, their table-like shape provides increased awareness—i.e., "an understanding of the activities of others, which provides a context for your own activity" (Dourish and Bellotti, 1992)—, parallel interaction, and, therefore, support for social and collaborative activities (Mandryk et al., 2001), whose benefits in learning have been widely reported in the literature (Cohen, 1994; Johnson et al., 1981; Webb and Palincsar, 1996). As mentioned above, smartphones and tablets allow direct touch input, which is very straightforward to kids (Hiniker et al., 2015; Nacher et al., 2015b), but is limited to what is happening on their small screen (Gray et al., 2015), leaving the space above and around the devices underused. The use of this space has several potential benefits: Firstly, it enables the use of tagged tangible elements which can be recognized by computer vision systems and may provide an easy-to-understand physical clue of an action, an item, or a character within a game. Secondly, these tangible elements may be used as containers of digital information that can be seamlessly moved across devices by simply performing an interaction in the air. Thirdly, the use of tagged elements in the air allows for parallel interactions in which the user who performs a given action can be identified. This would prevent children from having to identify themselves before starting an action in collaborative scenarios. Finally, as a result of actions or items being associated to physical elements that are easily moved from one device to another, physical activity would be encouraged which is a key factor in children's development (Tomporowski et al., 2011) and is beneficial for supporting the construction of a positive social space for collaborative learning (Malinverni and Burguès, 2015), thereby avoiding the problems identified by Seitinger (2006), who points out that this type of device does not encourage full-body motion.

However, despite these benefits, to our knowledge no studies have evaluated whether these mid-air interactions based on tagged elements are feasible and usable by young children or have reported the level of precision that they can achieve with them. This is a mandatory and fundamental requirement before table-like MDEs are built for educational purposes that rely on handheld devices using this type of interaction. Therefore, the main contributions of this work are, first, the motivation and discussion of a new category of educational games based on tablet MDEs, in which tagged mid-air interactions would complement multi-touch; second, an evaluation in a sample of sixty children aged 6-12 of the level of the precision of interactions above the devices using MarkAirs (Garcia-Sanjuan et al., 2015c, 2016a), a mid-air interaction technique relying on fiducial markers attached to cards; and finally, the evaluation of the children's subjective impressions of this new type of technology, including the possibility of its being implemented in new engaging collaborative multi-display learning environments.

6.2 Related Works

Several studies have previously explored the use of tablet-based MDEs, although they concentrate on the use of the devices as private interaction spaces in which seamless interactions never, or only occasionally, occur between them. For instance, Yuill et al. (2013) designed an MDE which encourages children to play a game with their parents in which they draw pictures collaboratively. Each user draws a body part on their tablet and then exchange devices to complete each other's artworks. The work by Sørensen and Kjeldskov (2012) consists of a multi-device music player in which the control interface is distributed among several smartphones, but each user interacts only on one device, and no elements are transferred between them. The studies by Luchini et al. (2002) and Mandryk et al. (2001) do allow passing information between the devices through their infrared ports, the former to encourage children to collaboratively create and explore concept maps, and the latter to teach them genetic concepts through a game in which all the users collaboratively create a fish with certain genetic traits. Pass-them-around (Lucero et al., 2011) is another example in which multiple smartphones are arranged on a table to explore and share photos collaboratively. If put close enough, each device detects the relative position of the others by embedded radio tracking technology, allowing photos to be transferred to another phone by means of a fling gesture.

None of the above examples consider interactions above the device, either because information is only occasionally transferred between devices, because several users do not interact on the same device simultaneously, or because tangible elements are not used to convey the meaning of a given action or to act as containers of digital information that may be seamlessly transferred between devices. In this respect, several studies have addressed the use of around-device and mid-air interactions to support these requirements. Some of the existing approaches enable this type of interaction in handhelds, either by using fingers and hands (e.g., Jones et al., 2012; Kratz et al., 2012; Rädle et al., 2014), by wearing special rings (e.g., Hasan et al., 2013), or by using other handhelds (e.g., Woźniak et al., 2014). However, these works need the careful installation of calibrated external hardware (cameras or depth sensors) that introduce an additional cost and complicate the implantation of the settings in actual environments. Others prefer using the devices' built-in sensors, such as compass (e.g., Ketabdar et al., 2010) or camera (e.g., Garcia-Sanjuan et al., 2015a,c, 2016a). Whereas the former is more robust to occlusion than optical solutions, it is not possible to identify the source of a given interaction, which would be a desirable feature in a collaborative multi-display game, in which each player's actions could be tracked and acted upon (e.g., by maintaining a score). In addition, none of these solutions has been evaluated with children to measure the level of precision that can be achieved when fine-grained mid-air interactions such as translations, rotations and up/down gestures are required. Therefore, it cannot be argued that these systems are suitable for building cost-effective and usable future MDEs for game-based educational scenarios that rely on mid-air interactions.

For our purposes, we decided to disregard any additional external hardware that would result in expensive settings and could complicate the implantation of the system in a real environment, and also because in the future we want to build ready-to-play systems that do not require any previous calibration or include additional hardware components that could be accidentally manipulated by children. Among the existing approaches, in this work we make use of MarkAirs (Garcia-Sanjuan et al., 2016a) for several reasons: a) children are accustomed to playing with cards and trading card games have also been successfully used in learning contexts (Steinman and Blastos, 2002); b) using the same technology we can attach the same fiducial markers to other kind of toys to enable tangible user interfaces, which are intuitive and natural for kids (Strawhacker and Bers, 2014); c) the proposed markers can be tracked even if they are partially occluded; d) a virtually infinite number of markers can be used because they consist of arbitrary lines drawn on a card which could even be created by the children themselves; and e) a marker may even be a meaningful photograph which can represent a mapping between the card and the digital information it is associated with (e.g., if designers want a card to contain a game character, the marker could be a picture of the character itself).

6.3 Building Multi-Display Educational Games with MarkAirs

This section describes the characteristics of a new brand of educational multi-display games that can be created with MarkAirs. These games foster collaborative scenarios, the use of physical artifacts, the exploration of the physical world above and around the surfaces, and may also be used to promote physical exercise.

These environments are cost-effective since the only technological components they require are tablets with a built-in front camera and internet connection, which are now widely used. To run MarkAirs, the only additional components needed are some fiducial markers attached to common cards, to other physical objects, or displayed in a smartphone or another tablet. The markers are then tracked by MarkAirs computer vision software, which maps their pose to the position and orientation of game components, or to actions that are triggered by a certain gesture as shown by the authors of this technique in (Garcia-Sanjuan et al., 2015c)[1]. In order to build an MDE, children bring their own tablet and tagged objects

[1]See video at: `http://dl.acm.org/citation.cfm?id=2823480` (source materials)

and start playing in a way in which all of them can access any tablet in the environment, take them to another location if they please, and seamlessly transfer or control game components using MarkAirs.

Two examples of games that could be built with this technology are described next. In both of them, the transference of virtual elements between tablets is a cornerstone feature which is achieved as follows: Each marker acts as a container which is initially "empty." When placed above a tablet, it displays an open hand that serves as a cursor; the user can then move it by moving the card left/right and forwards/backwards on a horizontal plane parallel to the device. When the virtual hand is on the target element, the user lowers the card and makes the hand close over the object. When fully closed, the element has been "grabbed" and is "contained" in the card. To release the object, the procedure is the following: the user moves the card over another tablet and then "pours" its contents into it, with the hand cursor closed. The player can now move the element around and also rotate it by means of a yaw rotation of the card. To release it, the player raises the card, provoking the virtual hand to open which "drops" the object. This type of game could be played in this environment to teach children associations between concepts, and the specific contents of the game could be defined by the instructor according to the educational aim of the activity. The procedure of the game is as follows: several tablets are arranged across the room, and each one contains a collection of elements related to the lesson's topic; each student is given a "container" card with an ID encoded in its marker and then a special "target" element appears in one of the tablets and starts moving around. Since all tablets are connected, this object can exit the device it is currently in and enter another. This target is related to some other objects in the collections distributed across the devices, and the purpose of the game is for the children to "grab" elements that share a relationship with the target and drop them into the tablet in which the target element is displayed. This procedure can be repeated as many times as the teacher desires. To foster collaboration many small groups can be formed, so that each group has to jointly find the elements. Specific educational subjects that could be taught in this game include: animals (collection items) that eat a certain type of food (target), the (collection) items needed to plant a tree (target), etc. Since each player would be identified by the card, the system could inform the teacher's tablet about each student's mistakes, allowing subsequent individual reviews.

Another, less generic, example is a game to collaboratively build jigsaw puzzles. In this case, several tablets are arranged on a table side by side, forming a board, and others are scattered across the room. Suddenly, one of the latter emits a sound and displays the picture to be built, which the children can carry around, while the other tablets populate with different pieces of the puzzle. The children are encouraged to move around the room looking for the pieces, "grab" them, and then bring them to the "board" where the puzzle must be completed. Collaboration is encouraged because they must all solve the same puzzle and have to coordinate and exchange information during the game. To promote collaboration even further, the process of joining two pieces must be conducted in pairs. Two pieces "grabbed" by two players with their cards must be placed together and if they match they will automatically join. Then the users will have to release the combined piece together by raising their cards simultaneously. Since each user is identified by their card, they can find out at the end of the game how many pieces they have assembled, and a score can be kept in order to improve motivation. By following the same interaction mechanisms as this jigsaw-puzzle game, another type of game could be designed to be used in chemistry lessons, in which children would have to bring together atoms to build molecules.

In all the previous cases, the mid-air manipulations performed require a certain degree of precision, as the children have to follow moving elements, rotate others, and perform up and down gestures to "grab" and "drop" objects. Our study therefore evaluated the precision that can be achieved by children using this interaction technique.

6.4 Evaluating the Precision of MarkAirs

The following reports on an evaluation study of the use of MarkAirs as a potential mid-air interaction technique for children. The study had two goals: a) to obtain insights into the user experience of the proposed interaction, and b) to determine the level of precision that can be achieved for the three gestures proposed in the previous examples, i.e., translations, rotations, and up/down movements. The overall objective was to control an object's position, orientation, and size by means of these manipulations[2].

6.4.1 Participants and Apparatus

Sixty elementary school children participated in this study, 56.67% of whom were males, with ages ranging from 6 to 12 years ($M = 8.95$, $SD = 1.87$). They were grouped by age, with each age group a comprising the ages in $[a - 0.5, a + 0.5[$. Table 6.1 shows how many participants were assigned to each age group.

The experiment was conducted with a 10.1" Android tablet having a resolution of 1280×800 pixels, and running the MarkAirs framework. Following the guidelines by Garcia-Sanjuan et al. (2015a), a video region of 1/9 the screen size is provided to the user serving as visual feedback about the position of the marker with respect to the camera. A 5×5cm marker was attached to a 6×9cm piece of cardboard, as depicted in Figure 6.1.

6.4.2 Tasks

A target 2D object (O_T) was to be manipulated by means of mid-air interactions in order to obtain a random position, orientation, or size of a reference 2D object (O_R), as Figure 6.2 depicts. Six different tasks were performed, three to evaluate

[2]See video at:
https://www.dropbox.com/s/blh4msfp5tlfhsh/tasks_with_MarkAirs.avi?dl=0

Table 6.1: Number of participants by age group.

Age group	#Participants
6	6
7	11
8	8
9	10
10	10
11	7
12	8

Figure 6.1: A child interacting with MarkAirs.

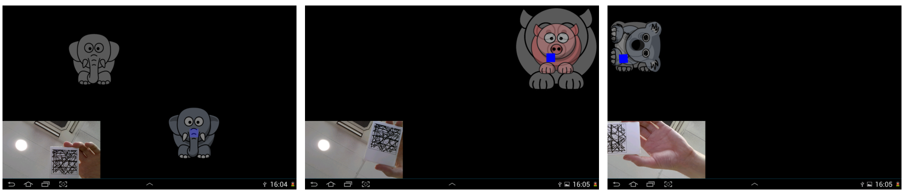

Figure 6.2: Manipulations evaluated: translation (left), rotation (center), and scaling (right).

the precision of each 2D manipulation in the termination phase (i.e., the precision with which the user was able to make O_T and O_R match), and three to evaluate the precision in the execution phase (i.e., the precision achieved continuously during the course of the manipulation).

Termination-Precision Tasks

These tasks are carried out in three steps: the first is the *acquisition* step, in which the participant uses the marker to control a small squared on-screen cursor and acquire O_T. The second is the *manipulation* step, in which the correct manipulation is performed to move O_T to O_R's position, orientation, or size (according to task). Once the system determines that O_T and O_R match within a certain error margin, i.e., at least 90% overlap (position/size) or less than 10% difference in their respective orientations, an acoustic feedback (a beep) is provided to the user and then the task moves on to the *precision measuring* step, in which the participant keeps O_T as close as possible to O_R (which remains static) for 5 seconds, while the system measures the precision (described below).

Execution-Precision Tasks

These tasks are conducted in two steps: the first is the *acquisition* step (as described above). Secondly, once O_T is acquired, there is a *manipulation/precision measuring* step in which O_R continuously and dynamically changes its position, orientation, or size (according to task) for 40 seconds at a variable pace. The participant must continuously keep O_T as close as possible to O_R while the system measures the precision.

6.4.3 Experimental Design

As stated above, each user performs the three manipulations (translation, rotation, and scaling) in two different precision measurement situations or phases (termination and execution). In order to avoid order and carryover effects, the manipulations are presented following a 3×3 balanced Latin Squares design. For each manipulation, the termination-precision task is first, followed by the execution-precision task.

The manipulation error during the *precision measuring* step is measured for each task as follows: the distance in pixels between the centers of O_T and O_R for the translation tasks, the difference between their orientation angles in degrees for rotation tasks, and the percentage difference between their scaling factors for scaling tasks. This error is calculated as the average of a number of samples obtained continuously during the *precision measuring* step.

The user experience was also evaluated through the Fun Toolkit (Read, 2008; Read and MacFarlane, 2006). The Smileyometer was administered before and after the task to compare expectation and actual experience; the Fun Sorter asked which manipulation (translation, rotation, or scaling) and which phase (termination—fixed targets—or execution—moving targets—) was more fun and easier to use;

and the Again-Again table asked whether the users wanted to play with each manipulation and phase again (i.e., with static and moving targets).

6.4.4 Procedure

The participants stand in front of the tablet placed on a table or chair, to suit the child's height. In the first stage the interactions are explained to the users, who then fill in the first Smileyometer on the fun they expect to have from the interactions. They are then given some time to train with the system to minimize learning effects. Once they report feeling familiar with the interaction, the experiment begins and the manipulation tasks are performed in the order given by the Latin Squares design. In the translation task, O_T is only sensitive to position changes of the marker (2 DOF), and the other two dimensions (size and orientation) stay the same as O_R. Analogously, when only rotation or scaling is evaluated O_T is only sensitive to those manipulations. Each interaction is repeated 3 times in which O_R's position, orientation, or scale is changed.

6.4.5 Precision Results

For each 2D manipulation, the users performed a total of 180 (60 users $\times$ 3 manipulations) interactions in the termination-precision task and 180 in the execution-precision task, so that each 2D manipulation was performed 360 times. Table 6.2 shows the average (and standard deviation) error measures for each type of manipulation, and Figure 6.3 depicts the evolution by age group of the different error values for each phase evaluated. Additionally, a mixed ANOVA with a Greenhouse-Geisser correction was conducted for each manipulation, with the phase (termination vs. execution) as a within-subjects factor and the students' age group as a between-subjects factor ($\alpha = 0.05$). The results showed a significant effect of the phase on the precision error for translation manipulations ($F_{1,164} = 99.800$, $p < 0.0005$), rotations ($F_{1,164} = 74.844$, $p < 0.0005$), and scaling ($F_{1,164} = 8.632$, $p = 0.004$), with the termination phase outperforming execution in terms of precision.

Also, the age group effect was statistically significant on translation ($F_{6,164} = 15.338$, $p < 0.0005$), rotation ($F_{6,164} = 8.917$, $p < 0.0005$), and scaling ($F_{6,164} = 4.826$, $p < 0.0005$) manipulations. However, even though Games-Howell post-hoc tests revealed that children of 9 or older perform translation tasks with significantly

Table 6.2: Average (and standard deviation) errors for each manipulation (in columns) and phase (in rows).

Phase	Translation error (px.)	Rotation error (deg.)	Scaling error (%)
Termination phase	27.13 (15.99)	8.41 (11.98)	4.97 (10.28)
Execution phase	45.07 (27.96)	20.89 (19.14)	7.67 (9.12)

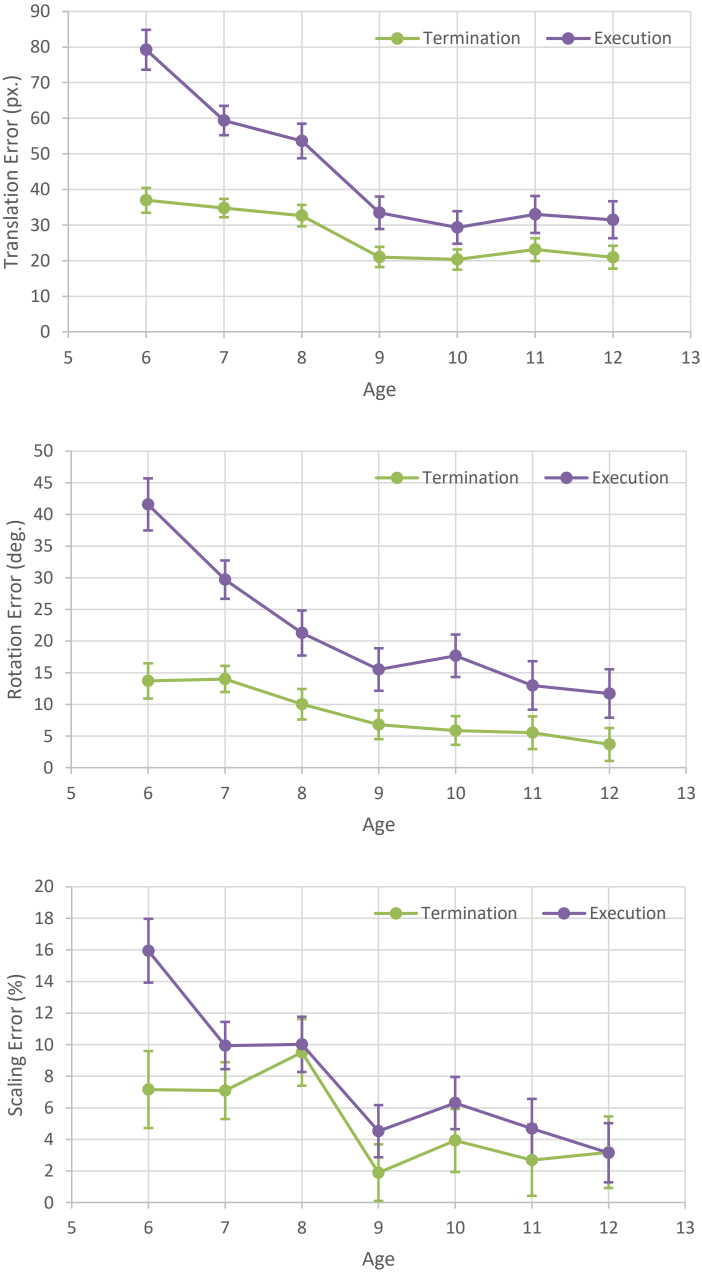

Figure 6.3: Evolution of translation (top), rotation (center), and scaling (bottom) errors by age group for each phase evaluated.

more precision than the younger ones ($p < 0.026$), the age threshold is not clear for the other two manipulations, due to the larger standard deviations in the data. Nevertheless, a Spearman's rank order correlation revealed that there was a significant negative correlation between age and both rotation and scaling errors ($p < 0.0005$), meaning that those precision errors also tend to decrease with age, as Figure 6.3 also shows.

Furthermore, the interaction between the age group and the phase factors was also significant for translations ($F_{6,164} = 5.251$, $p < 0.0005$) and rotations ($F_{6,164} = 2.678$, $p = 0.017$), which means that the errors evolve differently across the age groups in each phase. Indeed, as can be seen in Figure 6.3, the translation and rotation errors in the execution phase decrease much more rapidly than in the termination phase as age reaches 9 years old. From this age on, there are no significant differences between the errors in rotation ($p > 0.148$) and translation ($p > 0.881$) manipulations. The evolution of scaling errors in both phases is not significantly different ($F_{6,164} = 1.114$, $p = 0.356$), and no significant differences can be found between scaling errors for children aged 9 to 12 ($p > 0.809$).

6.4.6 Qualitative Results

This section reports the results obtained from the Fun Toolkit questionnaires. Since a Kruskal-Wallis H test ($\alpha = 0.05$) did not report statistically significant differences in any dependent variable across the age groups ($p > 0.091$), the following analysis focuses on global scores for all the children evaluated.

The Smileyometer results showed high ratings by the children both before playing ($M = 4.79$, $SD = 0.45$) and after ($M = 4.95$, $SD = 0.29$), but a Wilcoxon signed-rank test ($\alpha = 0.05$) revealed a statistically significant change between the two ($Z = -2.714$, $p = 0.007$), meaning that the actual experience was rated significantly higher than the expectations.

The results from the Fun Sorters are shown in Table 6.3 and Table 6.4 for differences between manipulations and phases, respectively. The average score is shown for each manipulation and phase in the tables. This score was established by assigning 1 point to the best dimension for each construct, 2 points to the second best, and so on, so that the closer the score is to 1 the better it is.

Figure 6.4 shows the results of the analysis of the Again-Again table, in which the children reported their intention of playing again with each manipulation and whether they preferred following a target or bringing the marker into a static position/orientation/size.

6.4.7 Discussion and Design Implications

The results indicate that the manipulations evaluated can be performed by children with a fair level of precision in the termination phase. Indeed, on average, the error for translation tasks is 27.13 pixels, which, in a screen resolution of 1280×800 represents 2.12% and 3.39% of the screen's width and height, respectively. The error for scaling tasks is 4.97% of the reference object's size, which is also relatively

Table 6.3: Fun Sorter results for manipulations. Inside parenthesis, the mean score for each manipulation.

Measure	Better	Intermediate	Worst
Fun	Scaling (1.47)	Rotation (2.18)	Translation (2.35)
Easy to use	Translation (1.67)	Scaling (1.84)	Rotation (2.47)

Table 6.4: Fun Sorter results for phases. Inside parenthesis, the mean score for each phase.

Measure	Better	Worst
Fun	Execution (1.21)	Termination (1.79)
Easy to use	Termination (1.16)	Execution (1.84)

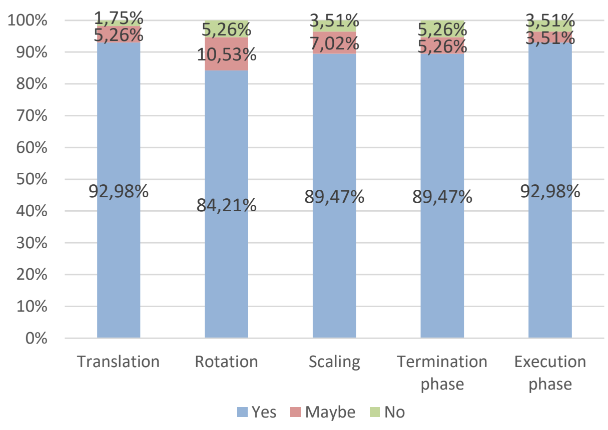

Figure 6.4: Results from the Again-Again table.

small. The mean error value for rotation manipulations is 8.41º, which represents 4.67% of the possible maximum error (i.e., 180º). These values show that the proposed interactions could be performed successfully by children from 6 to 12 with a static reference object.

The errors in the execution phase are significantly worse, which is understandable, since following a moving target is a more complex task. In this case, on average, the translation error is 45.07 pixels (3.52% and 5.63% of the screen's width and height, respectively); the scaling error is 7.67% of the reference object's size; and the rotation error is 20.89º (11.61% of the maximum achievable error). What these results imply for the future design of games involving mid-air interactions with MarkAirs is that, in general, the threshold to determine a successful match between an object being manipulated with respect to a reference object should be broadened when the latter is moving in the game space.

The effect of age also has a significant effect on precision, as errors decrease with age; nevertheless, from 9 years onwards no significant differences appear in the errors for any manipulation. Before this age, in spite of making more precision errors, children are still able to perform translations, rotations and up/down gestures successfully. Even when the errors are highest (translation/rotation in the execution phase for children less than 9) these errors decrease very quickly up to this age. These findings therefore suggest three main implications: First, that children of 9 years and older are able to perform fine-grained interactions with MarkAirs, regardless of whether the reference object is static or moving. Second, that even if children under 9 make substantially more errors in rotations and translations when the target is moving, they are still able to perform these gestures with fair precision when the target is still. Therefore, designers should probably consider larger success thresholds for translations and rotations when the target is moving, but not necessarily when it remains still. Finally, since scaling manipulations do not worsen differently with age, regardless of the level of mobility of the reference object, interactions involving this up/down gesture (e.g., the "grab" and "drop" mechanism described in previous sections) should be designed more coarsely for children aged under 9 regardless of the target object's mobility.

As for the user experience results, it is interesting that all the children liked considerably the interaction and the activity, regardless of their age. Even before playing they had high expectations and scored on average 4.79 over 5, but after playing they reported significantly more fun (4.95 over 5), rating the experience as "brilliant" almost unanimously. They rated the scaling manipulation as the most fun. Although this conclusion concerns the mid-air gesture they made with their hand and the effect it caused on the graphical elements on the screen, and cannot be extrapolated to other actions, we consider this type of gesture as promising for the design of other effects, such as "grabbing and dropping" elements or modifying some of the game's properties, as the authors of MarkAirs described by Garcia-Sanjuan et al. (2015c). Another surprising result is the fact that children rated translation manipulations as the least fun but the easiest to perform. This could be due to translations being less novel to them, since they are used to moving elements with the computer mouse but not to performing gestures that trigger rotation and resizing. It is also interesting to notice that kids report having more fun with a moving target, even when they perform worse in this condition and are aware of the fact (they consider it harder than having it fixed to a location). This suggests that designers should not rule out moving targets for the children to capture. Perhaps what they should do, taking into account the level of precision errors, is to design coarser-grained interactions for children under 9, as mentioned above. In short, these results show that MarkAirs can not only be used by children with fair precision, but it is also a fun way of interacting with tablets. Furthermore, after having tried it, more than 84% of the children (see Figure 6.4) are willing to repeat the experience using all the manipulations and phases evaluated.

It is worth mentioning some design considerations that arose from our observations during the experimental sessions. First is a limitation of MarkAirs itself, because, since it relies on optical tracking, it is sensitive to changes in lighting conditions, and in order to achieve a fluid interaction the marker above the device should be well visible to the tablet's camera, avoiding intense artificial light sources above the display. Second, we observed that the video region was seldom used and some participants even remarked its uselessness. This contradicts Garcia-Sanjuan et al. (2015a)'s findings, but may be explained because, in the present study, it is redundant since the users have another visual feedback in the form of the squared cursor and the object being manipulated. Third, prolonged sessions with MarkAirs should be designed to include multiple short interactions, as some kids reported arm fatigue and neck discomfort when performing the same interaction for a long time. This could also be mitigated by allowing the kids to place the tablet vertically and performing the interactions in front of it, which was preferred by some participants, especially during rotation manipulations, which they preferred doing vertically with the card. Finally, to make the games more engaging when moving targets are considered the system could be adapted to the users by speeding up or slowing down the targets, since some users complained that some targets moved too slowly for them.

6.5 Conclusions and Future Work

In this paper we describe a way of creating multi-display educational games using the MarkAirs (Garcia-Sanjuan et al., 2015c, 2016a) mid-air interaction technique. We have included examples of games that could be built with this technology, aimed at fostering children's collaboration and exploration of the physical world around and above the devices. We identified being able to perform fine-grained manipulations as a key requirement for such interactions and an experiment conducted with primary school children yielded positive results in this respect. Not only are children able to perform translation, rotation, and up/down gestures with fair precision, but they also enjoy playing with MarkAirs and are eager to repeat the experience.

In future work, we plan to implement the educational games suggested in this paper and study, on the one hand, the user experience of MarkAirs in an actual multi-display setting; and, on the other hand, the impact of the games on learning educational concepts and on collaboration. We will also consider introducing other physical components to the games that could make interaction more natural and contribute to a more exciting experience.

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Chapter 7

Evaluation of an Educational Collaborative Game Based on Cross-Surface Interactions with Fiducial Markers for Children in Primary School

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Abstract

Designing educational collaborative games for children is a popular research topic. The recent popularization of handhelds has allowed the design of multi-tablet experiences in which several devices share both a physical space and a logical workspace. However, interaction with these devices is often limited to a single screen and to the small area of the display, leaving the surroundings of the screen often underused. This work presents and evaluates a multi-tablet game for primary-schooled

children in which collaboration and physical mobility are encouraged. This game relies on a mid-air interaction technique to manipulate objects on screen and to coordinate interaction across the devices. Specifically, two studies were conducted: one to evaluate the feasibility and usability of the technique to perform precise gestures, focusing on differences of age; and another in a real classroom setting to evaluate the user experience and the ease of use and performance of the interaction in the game. Results generally show that the technique enables precise gestures to manipulate digital objects on screen, and that it was well received by students and teachers alike in the context of the multi-tablet collaborative game, even though some usability problems were detected. Design guidelines for the future design of activities with this type of interaction technique are also provided.

7.1 Introduction

Learning through play and serious games has been reported to be more effective than traditional instruction methods (Nacher et al., 2015a; Wouters et al., 2013). Handheld devices such as tablets or smartphones are in almost universal use nowadays and have numerous advantages that make them suitable for their use in educational environments with children, e.g., they support the inclusion of multimedia and interactive contents, they enable direct manipulations via touch instead of indirect input via mouse, they can be shared, they are considerably cheaper than other interactive devices such as digital tabletops, etc. Albeit handhelds have been designed mainly for private use, several recent works (e.g., Garcia-Sanjuan et al., 2015c; Rädle et al., 2014) have attempted to build Multi-Display Environments (MDEs, a.k.a., Multi-Surface Environments) in a way that several devices share a physical space and belong to the same logical workplace (Garcia-Sanjuan et al., 2016c). These MDEs have several benefits in terms of mobility and scalability, since devices can be moved around and users can add/remove them dynamically at will. Also, they enable parallel interaction and support socialization and collaboration (Mandryk et al., 2001), whose benefits in learning have been widely reported in the literature (Cohen, 1994; Johnson et al., 1981; Webb and Palincsar, 1996).

As mentioned above, smartphones and tablets allow direct touch input, which is very straightforward to kids (Hiniker et al., 2015; Nacher et al., 2015b), but is limited to what is happening on their small screen (Gray et al., 2015), leaving the space above and around the devices underused. The use of this space has several potential benefits: Firstly, it enables the use of tagged tangible elements which can be recognized by computer vision systems and may provide an easy-to-understand physical clue of an action, an item, or a character within a game. Secondly, these tangibles may be used as containers of digital information that can be seamlessly moved across devices by simply performing an interaction in the air. Thirdly, the use of tagged elements in the air allows for parallel interactions in which the user who performs a given action can be identified. This would prevent children from having to identify themselves before starting an action in collaborative scenarios.

Finally, because of actions or items being associated to physical elements that are easily moved from one device to another, physical activity would be encouraged. This is a key factor in children's development (Tomporowski et al., 2011) and is beneficial for supporting the construction of a positive social space for collaborative learning (Malinverni and Burguès, 2015), thereby avoiding the problems identified by Seitinger (2006), who points out that this type of device does not encourage full-body motion.

Even though several previous works have designed multi-surface collaborative games for children based on mobile devices (e.g., Luchini et al., 2002; Yuill et al., 2013), they seldom support multiple users performing cross-surface interactions between the devices. To our knowledge, no study has evaluated, in the context of an actual educational setting with children, the user experience of a mid-air cross-surface interaction technique and whether it can be used to design collaborative scenarios that also foster physical activity.

This work makes use of a mid-air interaction technique based on tagged cards called MarkAirs (Garcia-Sanjuan et al., 2016a,b). The reasons for choosing this technique are manifold: a) the system is ready to use, no calibration is needed, and the only additional hardware required besides the tablets are cards with a printed fiducial marker on them, therefore disregarding any additional external hardware that would result in expensive settings and could be accidentally manipulated by the children; b) children are accustomed to playing with cards and trading card games have also been successfully used in learning contexts (Steinman and Blastos, 2002); c) using the same technology we would be able to attach the same fiducial markers to other kind of toys to enable different types of tangible user interfaces, which are intuitive and natural for kids (Strawhacker and Bers, 2014); d) the proposed markers can be tracked even if they are partially occluded; e) a virtually infinite number of markers can be used because they consist of arbitrary lines drawn on a card which could even be created by the children themselves; and f) a marker may even be a meaningful photograph which can represent a mapping between the card and the digital information it is associated with (e.g., if designers want a card to contain a game character, the marker could be a picture of the character itself).

In this context, the contributions of this paper are the following: First, a study with sixty children aged 6-12 of the feasibility and usability of MarkAirs to perform precise fine-grained gestures to manipulate 2D elements on screen, focusing on the differences of age, and aiming to extract design guidelines for future uses of the technique. This is a fundamental first step before MarkAirs can be applied to multi-display games for children. Second, the design of a multi-tablet game with MarkAirs as cross-surface interaction technique to promote collaborative learning and physical mobility. And, finally, a study with seventy-eight children aged 9-10 about the user experience and the ease of use and performance of MarkAirs in the game.

7.2 Related Works

Several studies have previously taken advantage of handheld devices such as smartphones and tablets in order to stimulate physical mobility through games in educational contexts. Kiwi Mobile (Lee et al., 2016) is an outdoor mixed-reality game aimed at helping players learn how a fictional phone manufacturing company works. By using geo-localization, the physical locations the players move around are mapped to virtual learning nodes (e.g., an interview with a game character, newspaper articles, and other game artefacts) that are triggered and displayed on screen when a user arrives to a specific location. The game is played in pairs, each member having to visit different locations. After the game, they gather at the classroom to discuss and share ideas. Moving indoors, SecretSLQ (Fitz-Walter et al., 2012) aims to teach the purpose and functioning of a library. The players can team up and explore the library searching for QR codes to unlock clues and answer questions on their device. Even though these games aim to foster collaboration and socialization, they usually have one user interacting with their own device or, if several participants are gathered around the same display, interaction can be easily monopolized by one of them, making the others adopt a more passive role.

In detriment of physical mobility, others have put more emphasis in supporting collaboration and parallel interactions through tablet-based MDEs. However, these studies concentrate on the use of the devices as private interaction spaces in which seamless interactions never, or only occasionally, occur between them. For instance, Yuill et al. (2013) designed an MDE which encourages children to play a game with their parents in which they draw pictures collaboratively. Each user draws a body part on their tablet and then exchange devices to complete each other's artworks. Movers and Shakers (Mitgutsch et al., 2013) is another collaborative game to introduce youngsters to some communication difficulties that take place in a workplace. Played in pairs, each user is seated in front of the other and given their own tablet. Each player has a personal goal that is in direct conflict with their partner's, and the game encourages them to communicate and solve their opposing ideas in order to achieve a higher, common, objective. The work by Sørensen and Kjeldskov (2012) consists of a multi-device music player in which the control interface is distributed among several smartphones, but each user interacts only on one device, and no elements are transferred between them. The studies by Luchini et al. (2002) and Mandryk et al. (2001) do allow passing information between the devices through their infrared ports, the former to encourage children to collaboratively create and explore concept maps, and the latter to teach them genetic concepts through a game in which all the users collaboratively create a fish with certain genetic traits. Pass-them-around (Lucero et al., 2011) is another example in which multiple smartphones are arranged on a table to explore and share photos collaboratively. If put close enough, each device detects the relative position of the others by embedded radio tracking technology, allowing photos to be transferred to another phone by means of a fling gesture.

All the examples above restrict interaction with the devices mainly to touch, leaving aside interactions with tangible objects that have been shown to be very intuitive for children and promising to be used in learning activities (Nacher et al., 2016a; Price et al., 2003; Strawhacker and Bers, 2014). In this respect, several works have considered bringing tangible interactions to mobile devices. Chipman et al. (2011) present a game for young children to collaboratively learn about patterns using tablets and RFID-tagged objects. The children scan an object with the RFID reader attached to a tablet and then they paint on it with a certain color that identifies them. Later, when another child scans said object, they can draw on top of previous drawings, thereby making the painting collaborative. The game allows the players to be aware of what each child has made, and to communicate with one another to ask who is represented by a given color, however, the communication fostered here is quite naive, and even though the children collaborate to reach a common goal, they perform their tasks individually. Another example is by Georgiadi et al. (2016) with a mobile game to learn about archaeological fieldwork. The game is played in groups of four. Each group explores collaboratively a physical space looking for special objects (Bluetooth beacons) that, when approached to a tablet, trigger specific mini-games and activities on it. Even though the children can explore the environment conjointly, each group is given only one tablet, therefore restricting multi-user interactions and limiting collaboration.

All the works described above have in common that several users do not interact on the same tablet simultaneously or that information is never or only occasionally transferred between devices. In order to support these features, they would need some interaction mechanism happening outside the boundaries of the display to allow multiple users to interact on the same device without occluding the screen to the others, and a seamless transfer mechanism between devices, such as the use of tangible elements that would act as containers of digital information. In this respect, several studies have addressed the use of around-device and mid-air interactions to support these requirements. Some of the existing approaches enable this type of interaction in handhelds, either by using fingers and hands (e.g., Jones et al., 2012; Kratz et al., 2012; Rädle et al., 2014), by wearing special rings (e.g., Hasan et al., 2013), or by using other handhelds (e.g., Woźniak et al., 2014). However, these works need the careful installation of calibrated external hardware (cameras or depth sensors) that introduce an additional cost and complicate the implantation of the settings in actual environments. Finally, others prefer using the devices' built-in sensors, such as compass (e.g., Ketabdar et al., 2010) or camera (e.g., Garcia-Sanjuan et al., 2015a,c, 2016a). Whereas the former is more robust to occlusion than optical solutions, it is not possible to identify the source of a given interaction, which would be a desirable feature in a collaborative multi-display game, in which each player's actions could be tracked and acted upon (e.g., by maintaining a score). In addition, none of these solutions has been evaluated with children to measure the level of precision that can be achieved when fine-grained mid-air interactions are required. Therefore, it cannot be argued that these systems are suitable for building cost-effective and usable MDEs for game-based educational scenarios that rely on mid-air interactions.

Figure 7.1: Child interacting with MarkAirs on a tablet.

7.3 An Overview of MarkAirs: A Mid-Air Cross-Tablet Interaction

MarkAirs (Garcia-Sanjuan et al., 2016a,b) is an interaction technique performed above a tablet or smartphone and is conducted by handling a fiducial marker which, when in the field of view of the device's built-in front camera, allows a computer vision software to detect the marker and track its 6-DOF pose (position and orientation) in real-time (see Figure 7.1). Markers can be attached to physical cards, and consist of arbitrary drawings which are tracked by the natural feature tracking algorithms of VuforiaTM. These particular markers present several benefits: First, they can be tracked even if they are partially occluded (see the bottom-left corner of the tablet in Figure 7.1, which shows the image captured by the device's camera). Second, this system allows for a virtually infinite number of markers. And, finally, a marker can also be a meaningful photograph, which can be related to the digital information content that is associated with the card. With MarkAirs, users can perform mid-air gestures to manipulate on-screen 2D digital elements, e.g., by mapping the translation vector and/or the yaw rotation information of the marker to the element's XY position and orientation. Also, gestures can be made in the air to trigger specific actions in the tablet, e.g., by moving the marker up and down (Garcia-Sanjuan et al., 2015c). Markers can behave as containers of these elements, which can help to avoid cluttering on the screens and be seamlessly transferred across devices. Additionally, since each marker has an ID encoded, users performing certain manipulations can be identified, which can be useful in learning environments since teachers can keep track of the student's performance or progress. For this, the devices are connected to a server, which maps each marker with the element contained and additional information regarding the user and the specific application MarkAirs is used in.

Table 7.1: Number of participants by age group.

Age group	Participants
6	6
7	11
8	8
9	10
10	10
11	7
12	8

7.4 Study 1: Evaluation of the Precision of MarkAirs for Manipulation Tasks

Before being able to use MarkAirs in an actual collaborative game with children, it is fundamental to know whether it can be used with precision to manipulate 2D digital elements on screen, and from which age it is usable. Therefore, the following reports on an evaluation study of the use of MarkAirs as a potential mid-air interaction technique for children. The goal of the study was twofold: First, to determine from which age is the technique usable, appealing, and allows the children to make precise manipulations with it (namely, translation gestures, rotations, and up/down movements); and second, to determine design guidelines to modify the technique in order to create a MarkAirs-based multi-surface game.

7.4.1 Participants

Sixty primary school children participated in this study (twenty-six females and thirty-four males), with ages ranging from 6 to 12 years (M = 8.95, SD = 1.87). They were grouped by age, with each age group a comprising the ages in $[a–0.5, a + 0.5[$. Table 7.1 shows how many participants were assigned to each age group.

7.4.2 Apparatus

The experiment was conducted with a 10.1” Android tablet having a resolution of 1280×800 pixels, running the MarkAirs framework. Following the guidelines by Garcia-Sanjuan et al. (2015a), a video region of $^1/_9$ the screen size is provided to the user serving as visual feedback about the position of the marker with respect to the camera. A 5×5cm marker was attached to a 6×9cm piece of cardboard, as depicted in Figure 7.1.

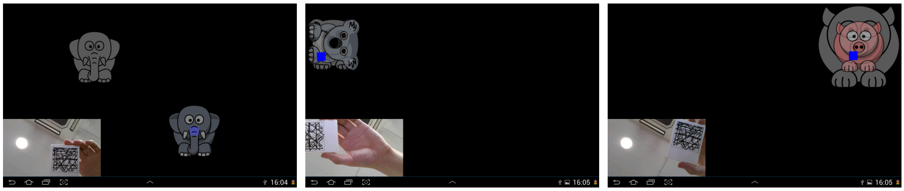

Figure 7.2: Manipulations evaluated: translation (left), rotation (center), and scaling (right).

7.4.3 Tasks

A target 2D object (O_T) was to be manipulated by means of mid-air interactions in order to match a random position, orientation, or size of a reference 2D object (O_R), as Figure 7.2 depicts. Translation manipulations consisted on performing gestures with the marker on a plane parallel to the tablet, rotations were triggered by means of yaw rotations, and performing up and down gestures provoked changes in the object's scale (down to decrease its size, and up to make it bigger).

Four different tasks were performed, three to evaluate the precision of each 2D manipulation in isolation (i.e., the precision with which the user was able to make O_T and O_R match), and another in which all three manipulations were combined into a single—more realistic—one.

These tasks were carried out in three steps: the first is the *acquisition* step, in which the participant uses the marker to control a small squared on-screen cursor and acquire O_T. The second is the *manipulation* step, in which the correct manipulation is performed to match O_T to O_R's position, orientation, and/or size (according to task). Once the system determines that O_T and O_R match within a certain error margin, i.e., at least 90% overlap (position/size) or less than 10% difference in their respective orientations, an acoustic feedback (a beep) is provided to the user and then the task moves on to the *precision measuring* step, in which the participant keeps O_T as close as possible to O_R (which remains static) for 5 seconds, while the system measures the precision (described below).

7.4.4 Design and Measurement Instruments

The manipulation error during the *precision measuring* step was measured as follows: the Euclidean distance between the centers of O_T and O_R in pixels for translation errors, the difference between their orientation angles in degrees for rotation errors, and the percentage difference between their scaling factors for scaling errors. Each error was calculated as the average of a number of samples obtained continuously during the *precision measuring* step. In order to avoid order and carryover effects, the isolated manipulations were presented following a 3×3 balanced Latin Squares design.

Figure 7.3: Smileyometer (extracted from Read, 2008).

The user experience was also evaluated through the Fun Toolkit (Read, 2008; Read and MacFarlane, 2006), a questionnaire consisting of three parts: the Smileyometer, the Fun Sorter, and the Again-Again Table. The Smileyometer (see Figure 7.3), a 5-point Likert Scale in the form of a Visual Analogue Scale (VAS), was administered before and after the task to compare expectation and actual experience; the Fun Sorter asked to sort the manipulations (translation, rotation, scaling, or all together) by fun and ease of use; and the Again-Again Table asked whether the users were willing to play with each manipulation again.

7.4.5 Procedure

The participants stood in front of the tablet placed on a surface whose height was adjusted to suit each child's height. In the first stage the interactions were explained to the users, who then filled in the first Smileyometer on the fun they were expecting to have from the interactions. They were then given some time (until they felt confident enough) to train all manipulations with the system to minimize learning effects. Once they reported feeling familiar with the interaction, the experiment began and the isolated manipulation tasks were performed in the order given by the Latin Squares design. In the translation task, O_T was only sensitive to position changes of the marker (2 DOF), and the other two dimensions (size and orientation) stayed the same as O_R. Analogously, when only rotation or scaling was evaluated O_T was only sensitive to those manipulations. Lastly, the task with all three manipulations combined was conducted. Each interaction was repeated 3 times in which O_R's position, orientation, and/or size was changed. Once the tasks were completed, the Smileyometer was administered again to record the perceived experience, as well as the Fun Sorter and the Again-Again Table.

7.4.6 Precision Results

For each 2D manipulation executed, the users performed a total of 180 (60 users $\times$ 3 repetitions) interactions in each modality (isolated or combined with the others). Table 7.2 shows the average (and standard deviation) error measures for each type of manipulation and modality, and Figure 7.4 to Figure 7.6 depict the evolution by age group of the different error values for each manipulation. Additionally, a mixed ANOVA with a Greenhouse-Geisser correction was conducted for each manipulation, with the modality as a within-subjects factor and the students' age

Table 7.2: Average (and standard deviation) errors for each manipulation (in columns) and modality (in rows).

Manipulation modality	Translation error (px.)	Rotation error (deg.)	Scaling error (%)
Isolated	27.13 (15.99)	8.41 (11.98)	4.97 (10.28)
Combined	34.26 (30.32)	6.74 (7.90)	4.63 (4.75)

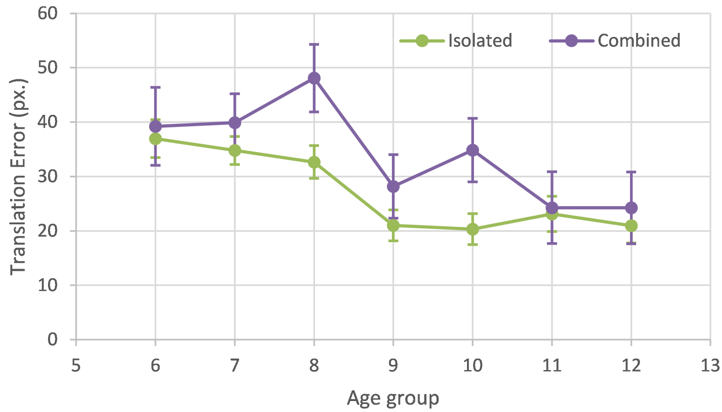

Figure 7.4: Evolution of translation errors by age group for each modality evaluated.

group as a between-subjects factor ($\alpha = 0.05$). The results showed a significant effect of the modality on the precision error for translation manipulations ($F_{1,164} = 8.41$, $p = 0.004$) with the isolated modality outperforming the combined one in terms of precision. However, no significant effect was found for rotations ($F_{1,164} = 3.739$, $p = 0.055$) nor for scaling manipulations ($F_{1,164} = 0.46$, $p = 0.499$).

On the other hand, the age group effect was statistically significant on all translation ($F_{6,164} = 4.226$, $p = 0.001$), rotation ($F_{6,164} = 2.582$, $p = 0.02$), and scaling ($F_{6,164} = 3.291$, $p = 0.004$) manipulations. Indeed, Games-Howell post-hoc tests revealed some significant differences between certain age groups (as shown in Table 7.3), but, because of large standard deviations in the data, no clear age threshold from which precision errors changed significantly could be extracted. Nevertheless, a Spearman's rank order correlation revealed that there was a significant negative correlation between age group and all three manipulation errors ($p < 0.0005$), meaning that precision errors tend to decrease with age, as Figure 7.4 to Figure 7.6 also show.

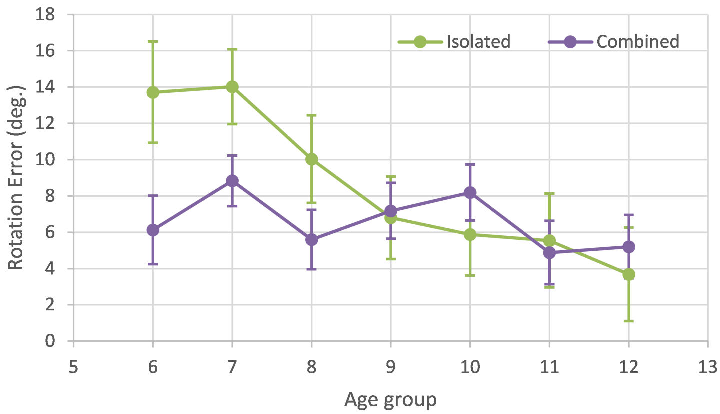

Figure 7.5: Evolution of rotation errors by age group for each modality evaluated.

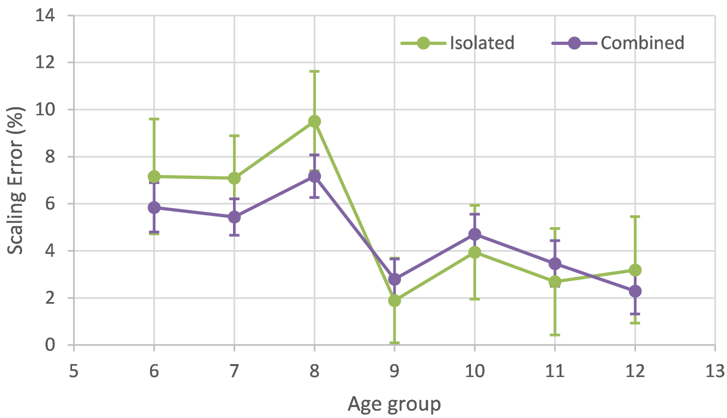

Figure 7.6: Evolution of scaling errors by age group for each modality evaluated.

Table 7.3: Significant precision error differences between age groups for each manipulation performed (the remaining combinations of age groups were not statistically significant).

Translations	**Rotations**	**Scalings**
6–9 ($p = 0.034$) 6–11 ($p = 0.017$) 6–12 ($p = 0.04$)	6–12 ($p = 0.037$)	6–9 ($p = 0.042$)

Table 7.4: Fun Sorter results for manipulations. Inside parenthesis, the mean score for each manipulation (the closer to 1, the better).

Measure	**Best**	**2nd Best**	**3rd Best**	**Worst**
Fun	Combined (1.54)	Scaling (2.23)	Rotation (3.00)	Translation (3.23)
Easy to use	Translation (1.80)	Scaling (1.91)	Rotation (2.69)	Combined (3.51)

The interaction between the age group and the modality factors was also analyzed and no significant effect was found on the dependent variable ($p > 0.072$), meaning that the errors do not evolve differently across the age groups for each modality: they decrease at approximately the same rate.

7.4.7 Results on Users' Impressions

This section reports on the results obtained from the Fun Toolkit questionnaires. Since a Kruskal-Wallis H test ($\alpha = 0.05$) did not report statistically significant differences in any dependent variable across the age groups ($p > 0.179$), the following analysis focuses on global scores for all the children evaluated.

The Smileyometer results showed high ratings by the children both before playing ($M = 4.79$, $SD = 0.45$) and after ($M = 4.95$, $SD = 0.29$), but an exact signed-rank test ($\alpha = 0.05$) revealed a statistically significant change between the two ($p = 0.012$), meaning that the actual experience was rated significantly higher than the expectations.

The results from the Fun Sorters are shown in Table 7.4 for differences between manipulations, including the combined modality in which all three manipulations were active at the same time. The average score shown in the tables was established by assigning 1 point to the best dimension for each construct, 2 points to the second best, and so on, so that the closer the score is to 1 the better it is.

Figure 7.7 shows the results of the analysis of the Again-Again Table, in which the children reported their intention of playing again with each manipulation, including all three combined.

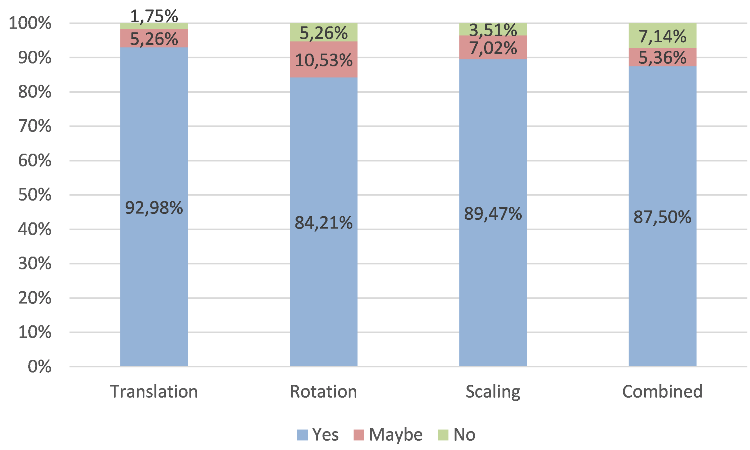

Figure 7.7: Results from the Again-Again Table for the precision study.

7.4.8 Discussion and Design Implications

The results indicate that each manipulation evaluated in isolation can be performed by children with a fair level of precision. Indeed, on average, the error for translation tasks is 27.13 pixels, which, in a screen resolution of 1280×800 represents 2.12% and 3.39% of the screen's width and height, respectively. The mean error for scaling tasks is 4.97% of the reference object's size, which is also relatively small. The average error value for rotation manipulations is 8.41º, which represents 4.67% of the possible maximum error (i.e., 180º). These values show that the proposed interactions could be performed successfully by children aged from 6 to 12.

When manipulating the object with all three operations combined, errors for rotation and scaling do not differ significantly from executing those manipulations isolated. They are significantly different, though, for translation manipulations, but still the average precision error for translations in the combined task is 34.26 pixels, which is relatively small considering that it only represents 2.68% and 4.28% of the screen's width and height, respectively. Having these small differences between modalities is to be expected since having to perform translations, rotations, and up/down movements at the same time is more demanding. Taking into account that the combined tasks were performed after the isolated ones, the fact of results not showing any significant differences for rotation and scaling manipulations could be explained by this extra time to practice the participants had. This suggests that perhaps with more training the precision errors could be reduced even further.

The effect of age also has a significant effect on precision, as errors tend to decrease with age. Even though there is no clear age threshold from which precision is significantly better, results suggest children aged 6 perform generally worse than the ones aged 9 or older, mostly for translation manipulations. This indicates that, in case of designing future activities with MarkAirs for children around 6 years of age, designers should consider larger success thresholds.

As for the user experience results, it is interesting that all the participants liked considerably the interaction and the activity, regardless of their age. Even before playing they had high expectations and scored on average 4.79 over 5, but after playing they reported significantly more fun (4.95 over 5), rating the experience as "brilliant" almost unanimously. Even though they rated the combined manipulation as the most difficult to use, they considered it the most fun; and, surprisingly, translation manipulations were rated the least fun but the easiest to perform. This could be due to translations being less novel to them, since they are used to moving elements with the computer mouse or by dragging gestures in touch devices, but not to performing gestures that trigger rotation and resizing. Although these conclusions concern the mid-air gesture they made and the effect it caused on the graphical elements on screen, and cannot be extrapolated to other actions, we consider the evaluated gestures as promising for the design of other effects, such as modifying some of the game's properties, as described by Garcia-Sanjuan et al. (2015c). In short, these results show that MarkAirs can not only be used by children with fair precision, but it is also a fun way of interacting with tablets. Furthermore, after having tried it, more than 84% of the children (see Figure 7.7) are willing to repeat the experience using all the manipulations evaluated, both isolated and combined.

It is worth mentioning some design considerations that arose from our observations during the experimental sessions. First is a limitation of MarkAirs itself, because, since it relies on optical tracking, it is sensitive to changes in lighting conditions, and in order to achieve a fluid interaction the marker above the device should be well visible to the tablet's camera, avoiding intense artificial light sources above the display. Second, we observed that the video region was seldom used and some participants even remarked its uselessness. This contradicts the findings by Garcia-Sanjuan et al. (2015a), but may be explained because, in the present study, it is redundant since the users have another visual feedback in the form of the squared cursor and the object being manipulated. Third, prolonged sessions with MarkAirs should be designed to include multiple short interactions, as some kids reported arm fatigue and neck discomfort when performing the same interaction for a long time.

7.5 Study 2: Evaluation of a Multi-Tablet Collaborative Game Using MarkAirs

After finding MarkAirs appealing to children and a successful enabler of precise manipulations of 2D digital elements on tablet devices, a second study was designed to evaluate a multi-tablet game with MarkAirs to promote collaborative learning and physical mobility. The purpose of the study was twofold: First, to evaluate the experience of primary-schooled children with a multi-tablet collaborative learning activity using MarkAirs as interaction technique; and second, to evaluate MarkAirs' performance and ease of use in a real educational scenario.

7.5.1 Designing a Collaborative Multi-Tablet Game

Gamification, or gameful design, is defined by Deterding et al. (2011) as "the use of design elements characteristic for games in non-game contexts." Therefore, for the design of the collaborative learning game, the five game dynamics identified by Bartel et al. (2015), in accordance with the definition by Deterding et al., were taken into consideration. These dynamics are: constraints, emotions, narrative, progression, and relationships. Given that in terms of educational goals the activity had two purposes: to enable physical mobility and to foster collaboration, two constraints to the game were imposed. First, the game elements would be located on different tablets scattered in an open space to force children to move from tablet to tablet during game play; and second, to fulfill the goals of the game, children would have to request the assistance of their partners and act cooperatively. In terms of emotions, the game followed a competitive approach based on personal scores that would reward those children who would be effectively collaborating with others. However, the narrative and progression dimensions of the game were kept as simple as possible for children to understand quickly the dynamics of the game and not to force them to follow a linear homogeneous game resolution path. Finally, special attention was given to the relationships dimension by designing a game dynamic that would allow children to collaborate with as many other players as they would like. In this respect, the game strategy designed would force children to communicate information with others either by asking them about their game status or by collaboratively designing a joint game plan. The actual game designed is described below, highlighting each one of these dimensions.

The goal of the game (*narrative*) is simple: children were told to collaboratively match world monuments with the flag of the country they belong to. As concluded by the precision study described above, to avoid long continuous interactions with the technique that could cause arm fatigue in the children and to promote physical activity (*restrictions*), the game elements are distributed among several tablets scattered across the classroom (see Figure 7.8). This way children can move around searching for them, hence combining physical mobility with multiple short mid-air interactions on the devices. Using MarkAirs, they can "grab" the different game elements (i.e., flags and monuments) and move them within and between tablets. Each child is only allowed to grab one object at a time (*restrictions*), and they must find another student who has their matching pair (*relationships*). Then, the game tells them (via audio and visual feedback) whether or not they have matched the items correctly (*progression*), and assigns points to each child's personal score (*emotions*). If they matched the pairs correctly, both members (*relationships*) get one point; otherwise, they lose one point (*emotions*). The game items are represented by icons (drawings); upon success, they are shown an actual picture of the monument (*narrative*). The use or MarkAirs allows for the posterior review of the children's performance by the teacher, since each interaction is recorded.

Figure 7.8: Children playing the multi-tablet game using MarkAirs.

To perform the cross-surface interactions, each child is given a personal card with a fiducial marker recognized by the MarkAirs framework, which they can grab and manipulate game elements with. When the card is first shown to a tablet, it displays an open hand. This hand can be translated and rotated by moving the marker accordingly. By moving the marker down, the hand closes, being able to "grab" an item if it closes on it (see Figure 7.9-left). Then, this item gets attached to the marker and can leave the current tablet. When a user shows again their marker on another display, if it has an item attached, it will show it with the hand closed on top. By moving the card up, the hand opens, releasing any item it may have "grabbed". When two players think they have a correct pair, they bring their respective items close by holding their markers together over the device; then, the system evaluates them, shows them an actual picture of the monument upon success, and updates the score. To minimize unintentional evaluations provoked by two children manipulating elements on the same tablet, each item has a small red circle on one of its sides. Hence, if two users want to get evaluated, they must bring their respective items close making the red circles face each other. When they are close enough, a lightning animation (as shown in Figure 7.9-right) appears, and then both participants have to move their hands up to release their items. Following the guidelines from the Study 1 above, video feedback was removed in favor of maximizing the available screen space, since having the hand cursor as visual feedback makes it unnecessary.

In order to separate the effect of the multi-surface environment with the mid-air interaction technique from the game itself, two versions of the game were compared: a digital one described above and an analog one, serving as baseline for the comparison, in which the game elements were printed on paper. Both versions of the game had the same components, but they differed on how they

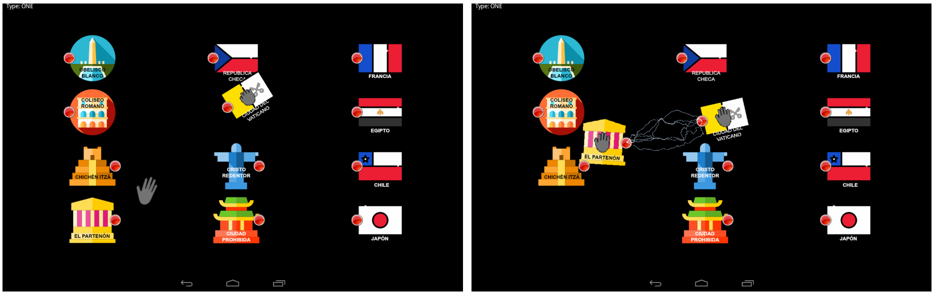

Figure 7.9: Two screenshots of the game with two markers (represented by hands) being shown to a tablet. On the left, a hand without an item and another with a flag “grabbed”. On the right, two hands with monuments placed close enough to trigger an evaluation from the oracle.

were interacted with due to the differences in technological equipment (digital tablets versus printed paper). These two versions of the game were compared in a real classroom setting in a summer school, with their teacher present.

7.5.2 Participants

Seventy-eight children (thirty-five females and forty-three males) aged 9-10 years participated in this study in the context of a summer school’s activity. They were not classmates since they originated from different primary schools in the region.

7.5.3 Apparatus

The study took place in a classroom. A total of one hundred thirty-five monument/country pairs were considered for the children to complete. For the analog version, the different items were printed on A5 sheets, and the teacher was provided with pen and paper as well as a blackboard and chalk to take notes about the students’ solutions and scores. As for the digital version, twelve 10.1” Android tablets with Internet access and running the MarkAirs framework were used, as well as a projector to display the students’ solutions and scores during game play in real time. Each child was provided with a 6×9cm piece of cardboard with a 5×5cm marker printed on one side and a number representing themselves in the other.

7.5.4 Measurement Instruments

The participants’ experience was evaluated via the Fun Toolkit (Read, 2008; Read and MacFarlane, 2006). The Smileyometer asked about the perceived fun and complexity of both versions using the following questions:

- How much fun did you have playing with the tablet version of the game?

- How much fun did you have playing with the paper version of the game?
- How easy to understand was the tablet version of the game?
- How easy to understand was the paper version of the game?

The Fun Sorter asked the children to select which version of the game they thought was more fun and with which one they thought they had obtained better performance. The Again-Again Table asked them whether they would like to play again with both versions of the game.

The students were also asked, for each version of the game, about their preference on making the pairs (either alone or with a partner). They were also asked to write down their general impressions (e.g., what they had liked best/worst, or what changes they would make to the game).

Additionally, the performance of MarkAirs in this game was evaluated by measuring how many pairs were completed in each version, and the technique's ease of use in this game was measured through the following questions using the Smileyometer:

- How easy was grabbing items on the tablet?
- How easy was moving/rotating items within the tablet?
- How easy was releasing items with your partner on the tablet in order to get evaluated?

7.5.5 Task and Procedure

The participants were split in seven groups consisting of ten members and one group of eight. They all played with both versions of the game, but in alternating order to avoid order and carryover effects: While half of the groups played first with the paper version, the other half started with the digital version. Each session lasted thirty minutes: twenty of game play and ten of reflection in which the teacher discussed with the children the solutions provided and answered doubts. After this, the participants moved to the other version of the game, and, upon completion of this second session, the questionnaires described previously were administered.

As described above, in the digital version of the game (see Figure 7.8), each child was given a card to manipulate the game elements. The card had a number on the reverse to identify the player, hence their progress and performance could be monitored by the teacher in real time through their smartphone via a web application. In the analog version (see Figure 7.10), when two children considered they had a matching pair, they consulted the teacher who acted as an oracle and told them whether they were correct or not, showed them the proper monument picture if they were, and registered the solution that had been presented for further analysis afterwards.

Figure 7.10: Participants playing with the analog version of the game.

After the game, in the analog version the teacher exposed their notes to the whole class to discuss; whereas in the digital version all this information was displayed on a wall display for everyone to see, as Figure 7.11 depicts.

7.5.6 Results

In general, the participants rated the experience very highly in terms of fun, with a mean score of 4.29 ($SD = 1.15$) for the digital version and of 4.58 ($SD = 0.80$) for the analog version. An exact signed-rank test ($\alpha = 0.05$) did not elicit any significant differences between versions ($Z = -1.690$, $p = 0.091$). As for the complexity of each game, both versions were perceived easy to understand, with mean scores of 4.04 ($SD = 1.24$) and 4.45 ($SD = 1.03$) for the digital and analog versions, respectively. However, an exact signed-rank test ($\alpha = 0.05$) revealed significant differences between the different versions of the game ($Z = -3.359$, $p = 0.001$).

As for the Fun Sorter results, 51.95% of the children considered the analog version of the game more fun, followed by the digital version (33.77%) and by having no preference (14.29%). Similarly, 64.94% of the participants perceived having performed better with the analog version, 25.97% with the digital one, and 9.09% with both of them equally.

Figure 7.12 depicts the results of the analysis of the Again-Again table, in which the children reported their intention of playing again with each version of the game.

Additionally, the participants generally expressed their preference for matching the elements collaboratively rather than individually, with 92.21% of the children expressing this for the digital version of the game, and 92.10% for the analog

Figure 7.11: Wall display showing the children's solutions in the digital version of the game.

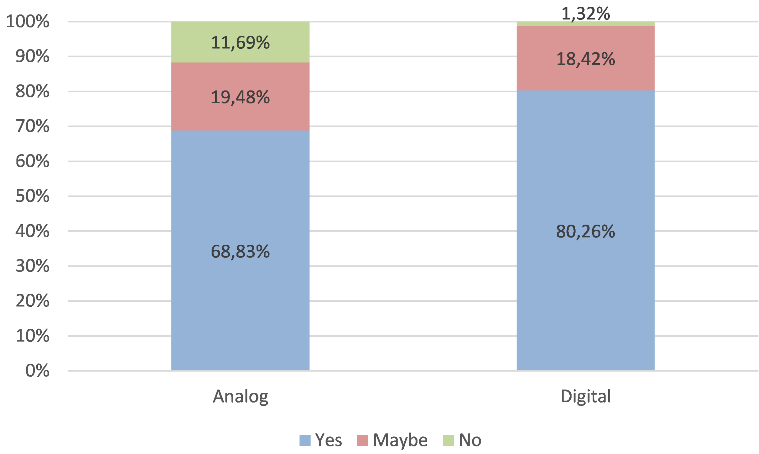

Figure 7.12: Results from the Again-Again Table for the game evaluation.

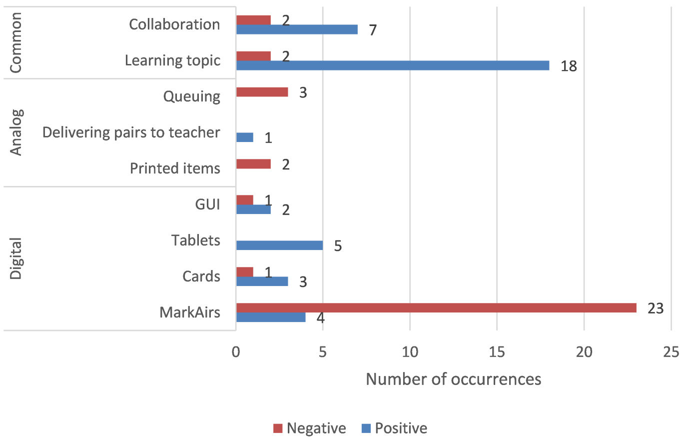

Figure 7.13: General impressions (positive and negative) of the children towards the game itself ("common"), the analog version, and the digital version.

Table 7.5: Ease of use scores for the different operations conducted with MarkAirs during the game. For each operation, whether it was conducted individually or in pairs is indicated in parenthesis.

Operation	**Mean score (and SD)**
Grabbing items (individual)	3.17 (1.33)
Moving and rotating items (individual)	3.69 (1.34)
Releasing items to get evaluated (in pairs)	3.40 (1.31)

one. They also pointed out several positive and negative impressions towards the game itself and both played versions. Figure 7.13 shows a summary of these with the number of children that expressed them. As it can be seen in the chart, MarkAirs received many negative comments, which were associated to tracking problems. The players also proposed some changes to make the game more appealing. These were associated mainly with their negative impressions (e.g., being able to build the pairs individually if they disliked collaborating with others, or improving MarkAirs' tracking). However, some of them proposed other changes, such moving the game outdoors, combining MarkAirs with tactile interactions, and building a hybrid version in which paper and tablets were combined.

Finally, with respect to MarkAirs in this game, the average number of pairs completed per session was 53.25 (SD = 7.67) in the analog version, and 25.63 (SD = 6.82) in the digital one. Table 7.5 shows the mean scores given by the children to the ease of use of the different operations that could be conducted with the mid-air interaction technique.

7.5.7 Discussion

The results indicate the participants generally enjoyed the game, particularly the learning topic chosen and building pairs collaboratively with other students. Indeed, the latter was supported by more than 92% of the users, regardless the game version (analog or digital). These findings suggest that collaborative games should be considered further in the future to design educational activities.

Both versions of the game were overall rated very highly in terms of fun, with ratings between "really good" and "brilliant" in both cases. Even though no significant differences were found on the ratings when they were asked separately how much fun they had had with each version, when asked explicitly which of the two was more fun, the majority opted for the analog version. This might be due to the participants finding this version less complex than the digital one, and having obtained better results with it. Indeed, with MarkAirs the children were able to make 51.87% fewer pairs than manipulating paper, and they were aware of the fact, as the Fun Sorter results reveal. This difference in performance was expected, since the interaction to join two game elements in the analog version was designed as simple as possible to serve as a baseline, and consisted on each member of the team grabbing a piece of paper and consulting the teacher. Even though this evaluation procedure caused the appearance of a queue, it was observed that the children sometimes leveraged it by having one of the team members always in line and the other picking items, which made them present their solutions quicker. Even though this was against the rules, building this strategy was product of collaborative work, and they did use the time in the queue to analyze and discuss their solutions. In contrast, making a pair in the digital version involved a more complex set of interactions with MarkAirs that inevitably took longer, despite not having to wait to know whether their solution was correct or not. In rough terms, during the time that took to build a pair with MarkAirs, two were completed in paper, which is not a poor performance considering that this was the first time the children were introduced to MarkAirs and were not given any time to train with it. Taking into account the results from Study 1 reported above about the precision of MarkAirs, with more time of exposure to the technique the results could improve.

The different manipulations conducted with MarkAirs (i.e., grabbing, moving and rotating, and collaboratively releasing items) were rated fairly well, with scores between "good" and "really good". However, the students evidenced some issues with the technique, mostly due to tracking loses, which made them angry sometimes and probably had an impact on the performance. As reported in Study 1, since the technique relies on optical tracking, it is very sensitive to lighting conditions, which could not be controlled in this study as it was conducted in the context of an actual summer school activity in an actual classroom. Another possible explanation to the tracking issues could be the fact that being in a high-paced activity in which the children were in a hurry to build pairs made them conduct very quick movements in front of the device's camera, which led to tracking loses. In this respect, the children proposed two changes to the interaction mechanism that could increase its performance. On the one hand, to combine MarkAirs with tactile interactions; on the other, building a hybrid version that combined tablets with paper. Whereas mid-air interactions could be used to seamlessly transfer game elements between surfaces, their manipulation on screen could be conducted via touch gestures. It is important to notice that manipulating tangible objects is present in the children's modification proposals, which suggests their willingness to use tangible user interfaces in this type of multi-display games.

Surprisingly, in spite of the poorer performance and of more children reporting the analog version as the most fun, the results of the Again-Again Table indicate that more children were willing to repeat the experience with the digital version than with the analog one, which makes it promising to explore other contents and interactions in the same context of collaborative learning games that support physical activity. The teacher was also fonder of the digital game, and praised the possibility of tracking in real time the children's progress. He confessed that the analog version consumed too much of his time acting as an oracle. It was observed that during the course of the digital version of the game the teacher was indeed tracking the children's performance and helping them. Moreover, during the reflection session, more discussion was observed in the digital version since the wall screen displayed all scores and solutions automatically, whereas in the analog version these results had to be read by the teacher or written on the blackboard first. This reveals one of the benefits of using technology in the classroom: helping teachers by relieving them of routine tasks and helping them focus on classroom dynamics and helping their students.

7.6 Conclusions and Future Work

This paper presented an evaluation of a multi-display game for primary-schooled children to foster collaboration and physical mobility based on tablet devices and mid-air interactions. Its goal was to collaboratively match monuments with the country they are in. MarkAirs was chosen as interaction technique for the game, a marker-based cross-surface mechanism that, by disregarding any complex hardware setup, is ready to use and cost-effective. Two studies were conducted: one to evaluate the usability and the precision that children aged 6-12 could achieve with MarkAirs, and another to evaluate the ease of use and performance of MarkAirs, as well as the experience of children aged 9-10, in the multi-tablet game deployed in an actual classroom.

Results from the first study indicate that children enjoyed performing manipulations with the technique regardless of their age, and that good levels of precision could be achieved with it to manipulate 2D elements on screen by means of translation, rotation, and up/down gestures with the hand above the device. Furthermore, data shows that errors decrease with age, and suggest that they could decrease as the users get more and more acquainted with the technique.

From the second study it can be concluded that the game was generally well received by both the children and their teacher. For the former it was a fun experience, and for the latter it provided a way of keeping track of the students' progress and performance in real time. The game using MarkAirs was compared to an analog version of the same game in which the children manipulated pieces of paper. Even though interactions with MarkAirs presented worse performance (by building 51.87% fewer pairs), this was expected since interactions in the analog version were designed as simple as possible to serve as a baseline and users had never had access to this interaction technique before nor did they have any time to train before the activity. Yet, manipulations with MarkAirs were rated between "good" and "really good" on average. Results also evidenced a usability problem with the technique caused by multiple tracking loses of the markers. These could be due to poor lighting conditions or to players moving the marker too fast in front of the tablet's camera. Despite these issues, more than 80% of the children expressed their desire to play again this game using MarkAirs. Overall, the results suggest further exploration of marker-based mid-air interactions on multi-display collaborative games.

As future work, further studies will be conducted to evaluate whether the performance of MarkAirs can be enhanced by increasing the exposure time of the children to the technique. Other types of markers will also be tested to increase the technique's robustness to poor lighting conditions and abrupt marker movements. Furthermore, following some suggestions from the children, other tangible elements will be considered besides the cards, and the combination of MarkAirs' mid-air gestures with touch will be explored.

Acknowledgments

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Part III

Tangibot: A Companion-Based Approach

Chapter 8

Design and Evaluation of a Tangible-Mediated Robot for Kindergarten Instruction

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Abstract

Entertainment technology increases children's engagement in educational activities designed to develop abilities ranging from collaborative problem-solving and cognitive attention to self-esteem. However, little research has been done on designing educational and entertaining interactive technology for kindergarten children (up to 5 years old). Furthermore, most of the work in this area has considered traditional input devices such as the mouse and keyboard, which are not suitable for these very young children. More recently, other more intuitive means of interaction (touch and tangible interfaces) and advanced educational artifacts such as robots have emerged. In this work we therefore present a joint collaboration between technologists and kindergarten instructors to design and evaluate a technological

platform using a mobile robot for kindergarten instruction, as well as an intuitive and user-friendly tangible user interface. The results obtained suggest the platform is not only usable by kindergarten children, but it also allows them to be fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity. In addition, the instructors reported that the system was well accepted and praised its versatility in use as a supporting tool for their everyday classroom activities.

8.1 Introduction

Children today are born in a technological era and are introduced to technology at a very early age. As a result, there are many examples that have proven the virtues of technology in even the earliest stages of learning programs. Entertainment technology in particular increases children's engagement in educational activities and kids using computers may acquire pro-social behaviors and develop collaborative problem-solving abilities, cognitive attention, and self-esteem (Liu, 1996).

Even though considerable research in this area involves primary school children—aged 6 to 11 years—(Africano et al., 2004; Antle, 2013; Yelland, 1994), less attention has been paid to (pre-)kindergarten (up to 5 years old) users, perhaps because their cognitive and motor skills are not mature enough to be participants in interactions with computers via traditional peripherals such as mouse and keyboard. However, in recent years, more direct and intuitive means of interaction for children have been sought and these have been mainly enabled by touch interfaces (Hourcade, 2007; Nacher et al., 2015b) and Tangible User Interfaces (TUIs), which present an added value in early childhood education "as they resonate with traditional learning manipulatives" (Strawhacker and Bers, 2014). On the other hand, the use of robots as an educational tool is gaining momentum. As Li et al. (2009) point out, robots capture the imagination of children and, consequently, "using robots to support teaching and learning . . . has become a popular research topic." Nevertheless, very few studies in this area target children as young as those considered in this paper. This motivates us to carry out further studies that contribute to understanding the challenges, limitations and opportunities of these technologies in the context of kindergarten learning.

In this context, this work presents a technological platform aimed at supporting learning activities for kindergarten children using a TUI based on graspable interactive elements and a mobile robot. The platform was designed iteratively in two phases. Phase 1 consisted of building the first version of the prototype after a preliminary discussion between the design team and educational research specialists on the basic technological features a tangible-robotic infrastructure should have. The goal of this prototype was to serve as a starting point for Phase 2, which involved interviews with nursery educators, who proposed alternative designs in order to make it more suitable for the target users and to facilitate educational scenarios that had not been envisioned previously. Another version of the prototype emerged from these two phases, which was then evaluated through an experiment with children from two local kindergartens in order to assess its usability and the impressions and behaviors observed in the participating children. Since several studies reveal gender differences in young children with respect to visual-spatial (e.g., Levine et al., 1999; Nacher et al., 2014a) and problem solving (e.g., Yelland, 1994) skills, the experiment studied whether boys and girls performed and reacted differently with/to the platform.

The results obtained suggest the platform can be used by kindergarten children, who were found to enjoy using the system and had high levels of flow (Nakamura and Csikszentmihalyi, 2008). The instructors also reported that it was well accepted and praised its versatility as a supporting tool for their everyday classroom activities.

In sum, this paper contributes to the field by providing an evaluation of a mobile robot controlled by user-friendly tangible elements in the context of kindergarten settings. Also, it reports instructors' insights about design requirements for such a platform and about the activities that can be conducted with it.

8.2 Related Works

The present work is influenced by previous research on Child-Computer Interaction. Traditionally, this area has focused on interaction with computers and, therefore, via the keyboard and mouse. Hourcade et al. (2007), for instance, study the impact of mouse size on precision tasks concluding that when designing for very young children one should devise specific interactions taking into account that their motor skills are not yet fully developed. Another similar experiment conducted by Liu (1996) concludes that, even though kids interact fairly well with the mouse, this device is not very intuitive for them since they instinctively try to make touch gestures on the computer screen. In a similar direction, Antle (2013) make a comparison between mouse-based and tangible interfaces to identify interaction patterns in children solving a spatial task. They observe that TUIs enable more exploratory actions, which in turn provide faster and easier ways of interaction.

On the other hand, others have explored in depth tangible-only interactions with children. Dekel et al. (2007) suggest that digitally augmenting a physical game such as using blocks to help children's spelling may have a positive effect on kids' enjoyment. Africano et al. (2004) present the design of an interactive table with tangible tools to foster co-located collaboration, which they identify as a key element for learning that has not been explored in detail. Their platform is evaluated by teachers but who do not participate in the design phase. As a result, some activities are estimated to be too complex for children, but the authors do not present an alternative design. In turn, Marco et al. (2013) also present a tangible-mediated tabletop for kindergarten instruction which is reported to trigger positive reactions from the children. With this platform, the kids engage in co-located activities by manipulating physical toys that have a fiducial marker attached that is recognized by the computer vision software of the tabletop. Although children were involved in the design process as testers, the teachers did not participate in this phase. Another interesting study is presented by Tsong et al. (2012) who propose a design for a tangible multimedia learning system in which QR codes are attached to objects the children are already familiar with. Children are induced to show the tagged elements to the camera of a laptop and, as a result, some appropriate related content is displayed on the screen. Their study concludes that their platform enhances children's enjoyment and learning performance.

Finally, there are other works that analyze the use of robots in early childhood education. Osada et al. (2006) present PaPeRo, a robot that could be used as a tool to teach manners, communication, etc. to elementary school children. Tanaka et al. (2005) present QRIO, a humanoid robot aimed at encouraging toddlers to move and dance. However, their interaction with the robot is very limited, and as their only task is dancing, the proposed platform is limited in terms of learning activities it may enable. Another interesting work by Soute and Nijmeijer (2014) presents an owl-shaped robot that plays story-telling games with children aged 4 to 6. The robot narrates a partial story which children must complete by showing some flashcards to it. The results of the game sessions show that the system is engaging for kids. Ghosh and Tanaka (2011) present a Care Receiving Robot (CRR) that adopts the role of the pupil and children act as teachers in order to learn English vocabulary. The experiments show that children are very motivated at first but tend to feel frustrated and bored if the robot gives right or wrong answers too often. Later, Tanaka and Matsuzoe (2012) suggested that, in general, learning is enhanced if the CRR is used and concluded that this robot is able to teach verbs to kids aged 3 to 6. In addition, besides training linguistic abilities, Takahashi et al. (2012); Tanaka and Takahashi (2012) design a TUI in the form of a tricycle to remotely control a robot, which, as suggested by Nacher et al. (2015a), could be used to develop spatial capabilities in young children. The authors later conduct an experiment (Takahashi et al., 2012) in order to evaluate the intuitiveness of the interface with respect to a video game controller, and conclude that, even though the participants were able to complete more tasks with the tricycle, no significant differences were found in terms of preferences between both tangible interfaces.

The above analysis reveals, firstly, a trend of usually considering interactions based on mechanisms other than tangible and robotic elements. Secondly, it shows that most works tend to focus on children aged 4 and over when considering their interaction with technology. Thirdly, it makes clear that instructors are not always participants in the design process of technology-based instruction environments. However, in our opinion they are a fundamental element who can provide a valuable contribution from their practical experience for the successful development of future kindergarten educational systems.

This work is a step forward in this direction and contributes to the field by evaluating an initial collection of design rationales obtained in close collaboration with kindergarten instructors and that should be taken into consideration when devising future learning ecosystems based on tangible and robotic elements for kindergarten children.

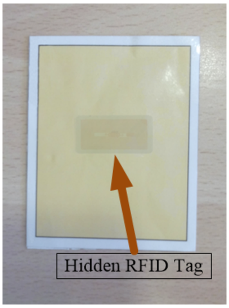

Figure 8.1: Card used to interact with the robot.

Our work shares several similarities with the commercial robot Bee-bot , which consists of a bee-shaped programmable robot that can move around the floor. Bee-bot accepts movement commands by pressing some arrow buttons on its back. However, in our opinion, its control interface presents an elevated cognitive load that could be an issue for its use with children less than 4 years old. First, in order to give it a movement command, at least two actions are required (one to select the direction and then press the "go" button); and, second, since the robot only traverses a short distance per command, should the children want to make it follow a long path, they would be required to give many more commands. Additionally, the platform can only move following straight lines, because it only supports 90º turns, and cannot support very well simultaneous interactions because of its limited interaction space and its incapacity to accept simultaneous commands. In addition, our design allows the specification of tangible elements with RFID tags encoding a pre-programmed set of sequential movement commands.

8.3 Platform Design

8.3.1 Phase 1: Initial Prototype

The design of the first prototype emerged from discussions between the design team and educational research specialists in order to obtain an initial concept design that would trigger further discussion about the actual requirements for the final platform. The first design iteration analyzed the best strategies to support Lentz et al.'s guidelines (2014), which suggest technology for children should: a) support children's mobility, b) provide interaction with the real world, c) enable socialization, d) allow adult supervision and intervention, e) provide a variety of sensorial experiences, f) offer symbolic play (i.e, using objects, actions, or ideas as a form of representation), and g) limit children's exposure to the device.

As a result, the first design consisted of two major components: a mobile robot and some small cards as a tangible mechanism to communicate with. The cards (see Figure 8.1) consist of two small laminated sheets with an RFID tag in between,

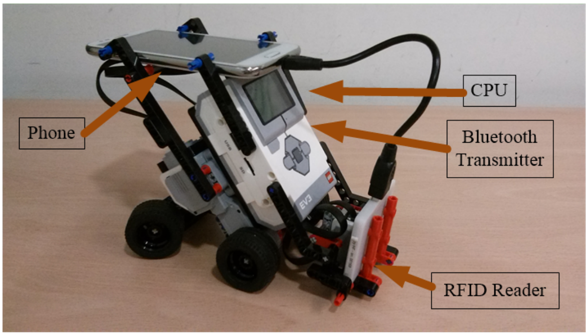

Figure 8.2: Detail of preliminary version of the robot.

which encodes movement orders (move forward, stop, turn left, turn right) that are given to the robot by bringing them close to its RFID reader (see Figure 8.2). The robot was constructed using the Lego™ Mindstorms® Ev3 platform, which facilitates rapid prototyping of multiple versions. It communicates by means of a Bluetooth link with an external mobile phone connected to an RFID reader. The phone is able to process the RFID tags enclosed in the cards, produces visual feedback and sends movement control commands to the robot by a Bluetooth link.

8.3.2 Phase 2: Review Sessions with Instructors and Design Refinement

Unstructured interviews were conducted with twenty-five educators from three different nurseries in order to obtain some insights into the design of the platform and the requirements to make it suitable for kindergarten environments. The participants had on average 17.27 years of experience ($SD = 10.33$) in the field of kindergarten education, ranging from 3 to 36 years and all were females. They were organized into seven discussion groups in which the procedure was as follows: Firstly, they were introduced to the different parts of the platform. They then watched a running application in which a card was shown to the robot which started to move until a different card made it stop. After the demo, they were asked open questions regarding the design of the different components of the prototype to encourage group discussion. These conversations were recorded and subsequently analyzed.

All the educators participating in the interviews expressed concerns about children dismantling the robot and putting the pieces into their mouths. As one teacher pointed out, "kids really have to touch everything." Some of them were also worried about the fragility of the robot (e.g., "this robot in my class wouldn't last a day"). And some advised us to change its appearance to make it more appealing to children. The following solutions were proposed:

Figure 8.3: Sticks with shapes representing the commands for the robot. From left to right: move forward (green), stop (red), turn left (blue), and turn right (yellow).

- Make the robot more robust and safe by enclosing it in a protective plastic case.
- Equip the robot with a pretty costume to give it a friendly plush toy-like look.
- Give the children a similar looking plush toy for them to manipulate, and bond with, which they can hold as they watch the actual robot move.
- Enable the robot to play audio files (music and sounds).
- Embed the RFID tags into "more manipulative" objects or change the materials of the cards into something "nicer" than plastic.

A second version of the prototype was produced after considering these comments. The cards were replaced by distinctive figures made of EVA foam, which contain the RFID tag. These shapes can be attached to sticks by Velcro® strips (see Figure 8.3) to make it easier for the kids to bring the shapes closer to the RFID reader. The commands these sticks represent, as can be seen in the figure from left to right, are: move forward, stop, turn left, and turn right. The proposed representations were obtained after discussions with educators who suggested that a representation based on shapes and colors would be favorable because these concepts were being taught to children. Besides, the use of arrows as a mechanism to describe turning commands was discarded because sticks could be approached to the robot from different points and with different rotations. As Figure 8.4 depicts, the robot's design was also modified by protecting it with a plastic case and attaching a Disney Wall-E plush robot to it. The RFID reader was moved outside the box and attached to the stuffed robot so that the kids could give it commands by putting the sticks to Wall-E's "chest."

Figure 8.4: Phase 2 version of the robot.

8.4 Potential Educational Activities

Besides the refinement of the platform's design, another result of the unstructured interviews with kindergarten educators was a discussion about whether the proposed robot and TUI could be used effectively in their everyday classes. In this respect, they found two different sets of activities that could be conducted with the platform, one for the youngest children (aged from 24 to 42 months), and another for the older ones (aged 43-60 months). They did not think such technology was appropriate for kids less than 24 months old. Specifically, tasks for the youngest should be more focused on psychomotricity and sensorial experiences (e.g., touching, tasting, smelling, etc.), whereas the activities envisioned for older kindergartners could involve more complex cognitive skills such as establishing mappings between concepts.

There are several common requirements for both age groups, such as supporting activities for language learning (e.g., by playing songs), and giving the option to undo or correct a given action. The requirements specifically proposed by the instructors for children aged under 42 months suggest, firstly, that the activities should have a very short duration, because children often switch their attention to other stimuli of the environment; secondly, that these activities should involve small groups (up to four or five kids) in order to have all children under supervision; and, finally, as stated by one educator, "the activities should focus on these three basic concepts: movement, lights, and sound." Some examples of activities pointed out by the instructors that could be conducted with the youngest age group are:

- Teaching children what a robot is and how it moves. They could watch the actual robot while playing with their own plush toy proxy.
- Teaching children where the source of a given sound is by driving the robot to its apparent location.
- Using a card or a tangible object that represents a concept (colors, animals, etc.) and making the robot find a representation of this element in the

classroom (e.g., a plush toy). In this case, the robot may be either directly controlled by children or able to move autonomously.

- Training psychomotor skills by making the robot move, possibly reproducing a sound to attract the attention of the children, and stimulate them to follow it. According to the instructors, this scenario could also be useful to teach children concepts such as "move/stop," "quick/slow," or "forwards/backwards," as they had seen the robot do during the demonstration.

Alternatively, teachers found additional more complex cognitive stimulation activities that could be supported with this technology for children in the second age group. In this case, the proposed size of the groups was increased to 7–9 kids. The educational activities suggested by the educators that could be performed with the platform can be summarized as follows:

- Moving the robot and making children repeat the movements afterwards. This could be done in the context of storytelling activities where, for example, the robot is looking for treasure and the kids must remember where the treasure is and repeat the robot's movements.
- Helping children associate concepts by placing some target objects on the floor and make them guide the robot towards one specific target. The selection of the element to be found could be done by the teacher telling them what to look for, or by making the robot reproduce a sound for the kids to identify. This way many concepts could be taught, such as colors, animals, professions, shapes, means of transport, etc. As one teacher expressed, in concept-association tasks "you can do anything, everything!"
- A path could be drawn on the floor for the kids to follow in order to teach balance, with the robot in front to motivate them.
- Teaching children how to make the robot move by remote control from a tablet or phone.

8.5 Evaluation

After finishing the second version of the prototype, it received the approval of the educators, and evaluation sessions were conducted to assess whether the children could effectively control the movement of the robot using the sticks. According to Druin's categorization of the various participatory roles children can have in the design of new technology (2002), our participants acted as users/testers. The study consisted of several play sessions in which observational findings were recorded.

8.5.1 Participants

Sixty kindergarten children participated in this study with ages ranging from 26 to 53 months. Their average age was 38.17 months ($SD = 5.94$). Since several studies

Figure 8.5: Kids playing with the robot during the experiment.

have found differences between young boys and girls in terms of performance in visual-spatial and problem-solving tasks (Levine et al., 1999; Nacher et al., 2014a; Yelland, 1994), the children were classified by gender and arranged in groups of four boys or four girls. As a result, fifteen different groups were evaluated, seven groups of males (aged on average 36.86 months, $SD = 4.90$) and eight of females (aged on average 39.31 months, $SD = 5.44$).

8.5.2 Procedure

Each session was conducted on a classroom floor area of 16m^2 (see Figure 8.5). First, a researcher showed the participants how the robot could be controlled by the sticks. Then, each kid in a group picked a stick, so that each one of them was in charge of a motion command, and practiced for one minute putting the foam shape close to the RFID reader and watching the robot move/stop accordingly. Once they had finished familiarizing themselves with the robot, they were asked to walk the robot from one point to another in the work space, where a Wall-E toy was placed. It was explained to them that they had to help the mobile robot reach its static plush friend, who was waiting for him so that they could play together. Once they made it reach its destination, the target toy was placed in a different location repeating this interaction 9 times for each group. A teacher supervised, guided, and encouraged the kids while they were playing, while two researchers took notes on the children's behaviors and impressions. After the session, the teacher, who knew the children's personalities and had experience in interpreting their behaviors and emotional states, reviewed the researchers' notes and completed or corrected them.

8.5.3 Method

Product of a previous discussion with the instructors, several observational dimensions were considered during the course of the activity regarding emotional, social, and interaction issues:

- *Positive impressions*: including all the pleasant and favorable reactions of the children towards the platform, namely, excitement, non-stop desire (i.e., not wanting the activity to stop), interest about the robot's technology, and astonishment.
- *Negative impressions*: consisting of all unpleasant reactions to the activity, such as frustration when they wanted the robot to move and failed to give the command properly, shyness, and lack of interest in the game.
- *Social behaviors*: According to Parten (1932), at the age of 2–3, children start to play side by side in the same activity in what she calls "associative play," which produces certain social involvement, until they learn how to collaborate. Hence, it is interesting to see how socialization and collaboration emerge when using the platform.
- *Interaction patterns*: referring to specific interaction strategies that children exhibited during game play.
- *Usability problems*: evaluating the main sources of interaction errors in our platform during the course of the activity.
- *Task completion*: If the task is not successfully completed, this dimension provides general insights into the fundamental reasons for failure.

8.5.4 Observational Findings

The kids played for a period of 10 to 24 minutes ($M = 15.0$, $SD = 3.92$), except for one group of boys that had to stop after 6 minutes because two of them started kicking the robot and the plush toy.

Emotional Issues

The first general impression observed during all sessions was the existence of some gender differences. In this respect, as shown in Figure 8.6, girls were shyer than boys when first approaching the robot, namely, they kept their distance and required the teacher to encourage them to make a first contact with the device. They also did not speak much during the course of the activity. One girl even refused to participate and had to be replaced by another classmate. However, this feeling was mitigated once they were introduced to the robot and watched it move, where some smiles appeared and shyness was, in some cases, replaced by astonishment (this impression was also more frequent in girls). The overall impression was that children had high levels of flow, as defined by Nakamura and Csikszentmihalyi

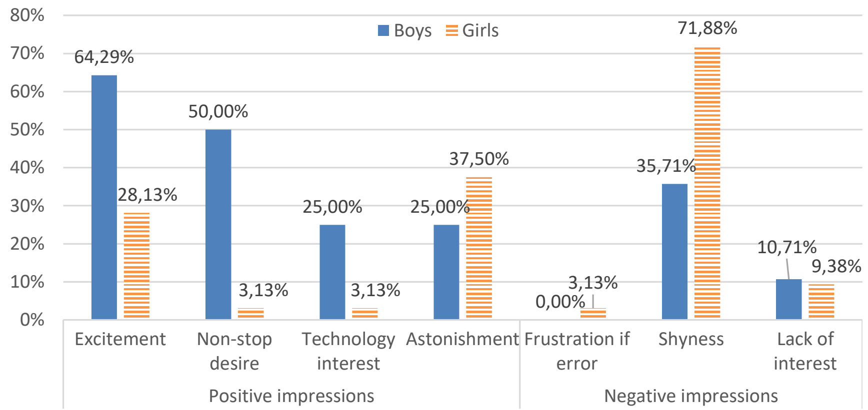

Figure 8.6: Positive and negative impressions observed in individuals (grouped by gender).

(2008), i.e., the majority of them were fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity with only 10.71% of boys and 9.38% of girls showing a lack of interest in the robot and the activity. In some cases, they tried to move the robot but failed in bringing the stick to the correct place where the RFID reader was located, but hardly any of the kids felt frustrated about this and continued in a mental state of flow, although boys seemed to enjoy the activity more. They were more excited and anxious to play (e.g., one of them, before the researcher finished explaining how the robot moved, took a stick and screamed "I want to, I want to!"). Boys were also more interested than girls on the technological components that composed the robot. They asked about the RFID reader and the smartphone ("There's a phone inside!," "It has a phone, why?"). And, finally, they were also less willing to stop the activity ("Again, again!," "Now where do we put it [the target plush toy]?").

Social Issues

The social behaviors observed and the proportion of the evaluated groups exhibiting at least one sign of a specific type of social behavior are summarized in Figure 8.7. The categorization of the observed behaviors was made in collaboration with children educators. Firstly, in many groups the figure of a leader appeared, who tried to direct the others (sometimes without success), and this was more frequent among girls (62.5% of the groups) than boys (28.57%) even of similar age. Secondly, 28.57% of the male groups showed at least one member who did not want to share the interaction with the rest (solitary play in terms of Parten's categorization), but this behavior was not observed in girls. This could suggest a higher degree of maturity among females. Thirdly, it was surprising that none of the female groups showed any trace of collaboration between its members, although

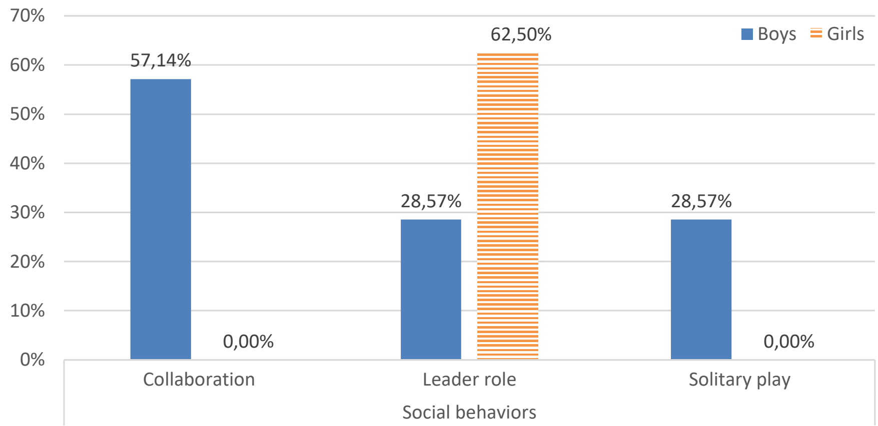

Figure 8.7: Group Social behaviors observed (grouped by gender).

this was a frequent behavior observed among the male groups (57.14%). Some traits of collaboration observed among the boys were: helping and correcting one another (e.g., a kid saying "Not like that" to another when the latter brought the stick to the wrong place), or coordinating their actions in order to complete the task ("Now you!," "Me, me, me!," "stop it!," "don't turn, it goes by itself").

The observed interpersonal skills were discussed with educators who confirmed these categories were consistent with everyday play with traditional toys in the classroom context. In addition, it is interesting to consider the work by Parten (1932) in observing and describing how social play develops in preschool children. In her studies she described development of social play into six categories: unoccupied behavior, onlooker behavior, solitary play, parallel play, associative play, and cooperative play. The first two categories are considered to be non-play behavior, and the last three are indicators of social participation. In terms of this categorization we may conclude that our platform enables associative and cooperative play because, as stated by Parten, the child plays with other children, the communication concerns the common activity, all the members engage in a similar activity and the group is organized in terms of different roles for the purpose of making some material product or striving to attain some competitive goal.

Interaction Issues

Besides performing the basic interactions to move the robot, other types of interaction were observed (see Figure 8.8). Although not very frequently, some boys and girls (7.14% and 12.5%, respectively) stopped playing and removed the protective plastic case from the robot in order to inspect the contents. Nevertheless, the kids were mostly focused on the task at hand, and a few of them were so immersed in the activity they started complementing the commands given with the sticks

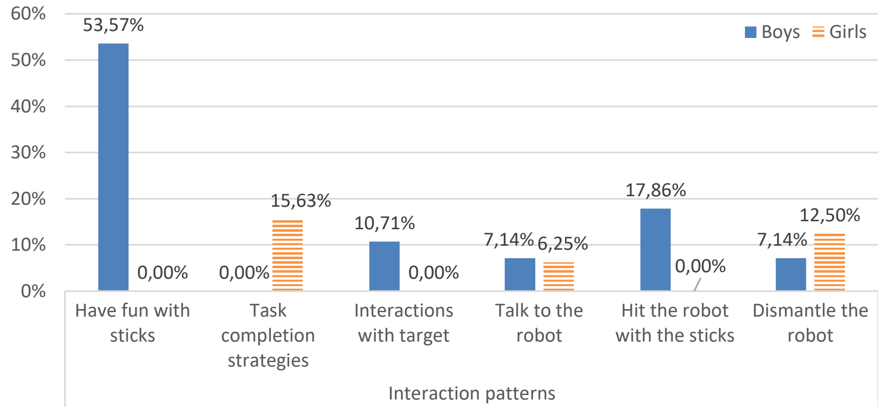

Figure 8.8: Individual interaction patterns (grouped by gender).

with oral instructions: "Come here, here!," "Turn, turn, turn!" Other differences were observed between boys and girls: whereas the latter were more patient, the former were generally more nervous and wanted to be constantly controlling the robot. With respect to this, 15.63% of the girls showed some strategic behaviors in order to complete the task, such as looking at the target while making the robot turn in order to know when they were facing each other so they could stop turning. On the other hand, some of the boys (10.71%) were so eager to use their sticks that they got confused and tried to give commands to the plush-only target instead of the electronic robot, because another boy was actually at that time interacting with the latter. Another reason supporting this claim of boys being more nervous and active than girls is that more than half of them (53.57%) had fun sword fighting with the sticks when they were not controlling the robot (e.g., it was moving forward or it was being controlled by someone else), and 17.86% of them repeatedly hit the robot with the sticks.

Regarding usability problems, the main reasons for interaction errors were also analyzed, and, as shown in Figure 8.9, the main reason for boys failing on giving a command to the robot was they were all interacting at the same time, which happened in 71.43% of the groups. This is probably related to boys being more active and nervous than girls, as explained previously. Also, in 14.29% of the groups there was at least one interaction that did not succeed because the boys blocked the robot with their own bodies once they had given it a command (e.g., by putting their foot on the same side they wanted the robot to turn to). Girls' interaction errors, however, were equally due to all of them interacting at once and placing the stick somewhere else than in front of the RFID reader (e.g., on the robot's head, back, etc.). This error, however, did not occur among the boys.

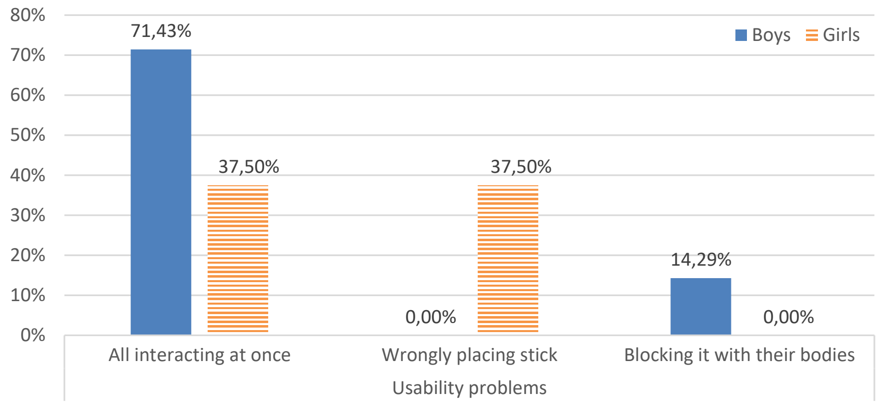

Figure 8.9: Usability problems (grouped by gender).

Task Completion

On average, the task of making the robot meet the plush toy was successful 71.43% of times for the boys, and 69.44% for the girls. However, when they failed it was mainly due to three reasons: the kids not knowing what to do, losing interest in the game, or holding and moving the robot manually without using tangible elements. The main reasons for the boys were, as Figure 8.10 depicts, not knowing what to do in 42.86% of the groups (e.g., the robot went into a wall and they did not know how to correct its course because the RFID reader was not accessible), and, to a lesser extent, losing interest in the task. The groups of girls presented higher percentages of these reasons than the boys. In 62.50% of them there was at least one case where they stood idly not knowing what interaction to perform next, in 37.50% of the groups lack of interest happened in one or more tasks, and, finally, in 12.50% of the groups there was a girl who did not make use of the sticks, and took the target and moved it to the robot, hence claiming she had completed the task.

8.6 General Discussion

The previous results can be analyzed according to several dimensions.

Firstly, it should be considered how effectively the technology can keep children in the mental state of flow which several studies recognize as a key factor in promoting learning. In this respect we may conclude that the platform was positively perceived by most children, who showed signs of amusement and stayed focused during the activity. Boys, however, showed a more explicit attitude towards the platform, as revealed by higher levels of physical spontaneity and joy, a higher number of observable complaints about having to leave the game, and a

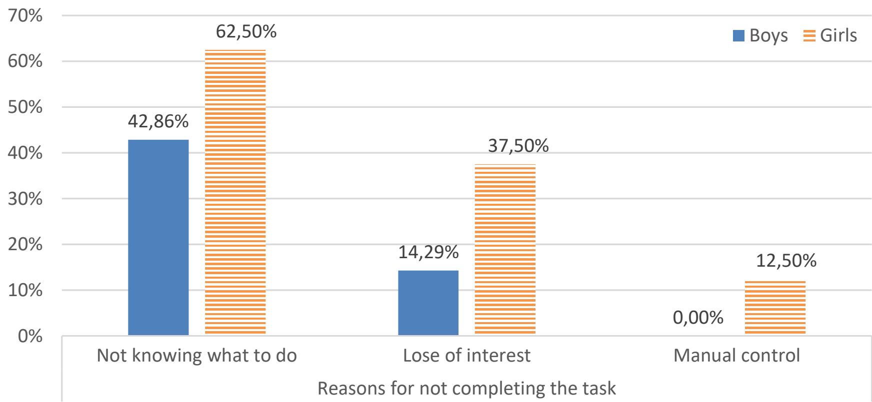

Figure 8.10: Reasons for not completing the task (grouped by gender).

higher number of inquiries about the robot's underlying technology. This is consistent with previous studies that analyzed gender differences in playful behavior among kindergarten children (Zachopoulou et al., 2004). This study reveals that boys are rated significantly higher than girls in measures of physical spontaneity and manifest joy. The fact that boys showed higher levels of interactivity with the robot is also validated by previous research, which suggests that girls tend to be more passive than boys, often playing inside (Smith and Inder, 1993) and are more likely to exhibit sedentary, constructive play (Rubin, 1977) while boys prefer to engage in gross motor and functional play (Rubin et al., 1976). Nevertheless, despite these previous works, it must be taken into account that gender behaviors may also be influenced by other factors such as parental gender stereotypes, previous experiences with technology, and previous experiences of the boys in the class.

Secondly, some interesting observations need to be discussed here on aspects of collaborative coordination and social behavior. Whereas girls showed a more hierarchical strategy, in which a "leader" emerged and directed the task (although their instructions were not necessarily heeded), boys showed more collaboration traits. This observation is not consistent with previous research (DiPietro, 1981) which found that boys' social interactions tend to be focused on dominance, with the role of a leader very often present, whereas girls have a stronger convention for turn taking with peers in decision making. This is also confirmed by Thorne (1993), who found that boys' play is usually hierarchical in nature, whereas girls' games are usually collaborative. However, these results were observed with older elementary school children, in whom, according to Lever (1976, 1978), sex differences emerge in the formation and organization of play. Therefore, it remains to be confirmed whether the social organization and roles observed in our experiment can be generalized for the earlier stages of development (pre-kindergarten and kindergarten). In this respect, further research with a higher number of groups needs to be done in order to confirm or refute this hypothesis.

It is also worth noting that in our experiment boys also showed a more dominant attitude, since they were more prone to conflicts with respect to having exclusive access to the robot's functionality. This agrees with previous research (Powlishta et al., 2001), which found girls more likely than boys to express behaviors that mitigate a conflict, whereas boys are more likely to exhibit different forms of heavy-handed behavior to resolve conflicting situations.

Thirdly, in terms of task completion and interaction problems it has to be pointed out that, even though the children were able to complete most of the tasks, there were some cases in which they did not know how to proceed, e.g., when the robot walked into a wall and made the RFID reader inaccessible. Some mistakes were also observed in girls concerning the correct placement of the stick when giving the robot a command. These mistakes more often observed in girls may be related to two cognitive issues. In the first place, as discussed by Yang and Chen (2010), the findings of numerous studies demonstrate that male children typically outperformed females in spatial ability tests, including spatial perception. In the second place, this may also be related to boys being usually engaged in more physical and spatial play, whereas girls are more involved in pretense (imaginary or simulated) game. i.e., they prefer fantasy play without the benefit of realistic props (Connolly et al., 1983).

Finally, another dimension worth considering is the educators' impressions. These generally expressed excitement about the platform and the possibility of using it as a support in their everyday classroom activities. Most of them acknowledged technology as a great motivating element for very young children. As a teacher expressed, it is very easy to capture their attention "simply by waving a paper in the air," but keeping them focused is more challenging. Technological devices cause attraction, hence retaining the kids' attention for longer periods of time. Furthermore, when they were asked whether this effect was caused by the devices per se or simply by being introduced to something new, some interviewees answered that, although the novelty factor had an important effect on the attraction, it did not seem to be crucial, because most children were already used to dealing with technological devices such as smartphones or tablets, and these still had the same captivating effect on them. Regarding our prototype in particular, some teachers remarked this platform would cause an interesting change of paradigm in their way of presenting new knowledge to the kids. In their opinion, this would be done in a more effective way by increasing children's focus on the activity. Almost all the educators praised the versatility of the platform, which could be used to teach a great variety of educational subjects and be used to make group activities (in contrast to using other more private devices such as tablets). Furthermore, some of them also appreciated the tangibility of the interactions in terms of being simple and understandable without requiring complex configurations on a digital display that would force educators to concentrate on the technology instead of on the children.

8.7 Conclusions and Future Work

In this paper we have presented the iterative design of a mobile robot controlled by a TUI to be used in the context of kindergarten educational activities. We have taken into account the insights and actual needs of nursery teachers in order to refine the design of the platform, and an evaluation has been made with actual children in order to test its usability. The results seem to indicate the platform causes high excitement among them, mostly in boys, and they generally have fun with it, in a permanent state of flow. In addition, the majority of them are able to complete the tasks, which is a reason to believe that the interaction is simple and intuitive enough for kindergarten children. Teachers also report good acceptance towards implanting the system in their classrooms, and they also foresee many activities that could be conducted with it, which makes this platform useful and versatile for kindergarten instruction.

In future work, we would like to explore in depth some of the behaviors observed, such as the relation between the appearance of a leader and collaboration between participants. Also, it would be interesting to go deeper into evaluating the goodness of the tangibility of the interaction versus remotely controlling the robot via other mechanisms, such as direct touch on a tablet or using a joystick, and also to study the effect on the experience of the shape of the tangible sticks compared to other different objects or materials. Furthermore, taking into account the educational activities proposed by the educators, more complex tasks will be devised in order to test whether the platform actually contributes to improving the learning of kindergarten children.

Acknowledgments

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We would like to thank the Universitat Politècnica de València, the Ituitu, and the Bambinos kindergarten schools for their collaboration during the development of this study.

Chapter 9

Evaluating the Usability of a Tangible-Mediated Robot for Kindergarten Children Instruction

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Abstract

The use of robots as an educational tool is particularly interesting because of their potential to support collaboration, their capability to trigger physical activity and their inherent attractiveness. However, despite their many benefits, few works have considered the use of robots with children aged under 6 years and those which are targeted at these very young children do not fully exploit the technology, since the designed robots are fixed in one spot and do not support collaborative and cooperative instruction. This paper therefore evaluates the usability of a tangible-mediated robot with eighty-six kindergarten children (2 to 6 years old) which was designed for collaborative kindergarten instruction. The results obtained proved the suitability of the proposed platform for children from the age of 3 years and

lays the foundation for developing new learning activities based on this technology for early childhood instruction.

9.1 Introduction

The new advanced learning technologies have evolved rapidly in recent years so that there are now many examples that prove the virtues of using technology in early childhood education. Entertainment technology in particular increases children's engagement in educational activities and kids using computers may acquire pro-social behaviors and develop collaborative problem-solving abilities, cognitive attention, and self-esteem (Liu, 1996). Recently, direct and intuitive means of interaction for young children have been developed and evaluated. Touch (Hourcade, 2007; Nacher et al., 2014b, 2015b) and tangible (Strawhacker and Bers, 2014) interfaces have been mainly used to fully exploit direct manipulation. Using robots as educational tools has also become a popular research topic, since their use captures the imagination of children (Li et al., 2009). However, very few studies evaluate the interaction between robots and children under 6 years old, hence further research needs to be done in order to understand the challenges, limitations and opportunities that robots may present in kindergarten learning contexts.

This paper evaluates how kindergarten children (aged from 2 to 6 years) interact with a tangible-mediated robot by guiding it through predefined paths. It focuses on both the precision such young users can achieve with a robot and also how this technology can be introduced to kindergarteners as an educational support. The contributions of the paper are manifold; firstly, the results revealed that the technology is suitable for children aged 3 years and older. However, the task evaluated was too complex for 2 to 3 year-olds. Secondly, the results revealed that there are different typologies of manipulation errors that decrease with age as children develop their cognitive and motor skills. Finally, the study revealed that most manipulation mistakes are made when children need to establish conceptual mappings between the available tangible interaction elements and the commands the robot supports.

9.2 Related Works

Several studies in the literature evaluate the use of robots by children. Unlike computers or interactive surfaces, tridimensional toys and robots have the capacity of being grasped, hence serving as a sort of Tangible User Interface (TUI), which presents an added value in childhood education "as they resonate with traditional learning manipulatives" (Strawhacker and Bers, 2014). All the studies involving robots and kindergarten children listed by Nacher et al. (2015a) reveal a current trend in developing robots targeted at kindergarten children. In addition, the results of the studies show that the robots evaluated cause excitement and engagement in children. Nevertheless, they do have some limitations that mean the robots cannot be fully exploited. In several of the studies the robots do not move around or use the entire classroom area for learning activities, since they are designed to be fixed in a particular location. In addition, some of the platforms evaluated do not allow the children complete control of the robot's movements, so that they only have a limited control of the activity. In cases when the robot's movements can be fully controlled, the interaction mechanism is limited to a single user, preventing scenarios in which children can work collaboratively and develop social skills.

To avoid these limitations, a previous work (Garcia-Sanjuan et al., 2015d) consisted of a joint collaboration between technologists and kindergarten instructors to design and evaluate Tangibot, a technological platform using a mobile robot for kindergarten instruction with an intuitive and user-friendly tangible user interface. The preliminary evaluation revealed that it is usable by kindergarten children and they enjoyed controlling the robot, were fully immersed and focused on the activity. However, the evaluation carried out was rather simplistic, as groups of four children (each carrying a stick to give commands) were asked to guide the robot from an initial point to a final location without any other restrictions. This paper extends this previous work in several ways; firstly, there is a precision restriction when using the robot. In the present study, the children have to make the robot follow a predefined path. Secondly, only two children guide the robot. This adds cognitive complexity, since each child must handle two sticks at a time (i.e. two different commands). This study is also more extensive and involves eighty-six children aged between 2 and 6, to check skill evolution with age.

9.3 Empirical Study

The goal of this study is to find out whether kindergarten children are able to guide Tangibot with high accuracy levels along predefined paths. Therefore, the main research questions of this work are formulated as follows:

- Are kindergarten children (aged 2 to 6 years) able to guide the robot along a predefined path?
- Is there a significant relationship between the time taken to perform the task and the children's age?
- Is there a significant relationship between the errors made and the children's age?

9.3.1 Participants

Eighty-six children aged between 2 and 6 years (M = 4.01, SD = 1.06) from a nursery and an elementary school took part in the experiment. In order to check how performance and precision in controlling the robot evolves with age, the participants were divided into four balanced age groups: 2–3, 3–4, 4–5 and 5–6 years old.

9.3.2 Procedure

The sessions were conducted on a $20m^2$ classroom floor area with two defined paths labeled with green cards. The paths were approximately 4.15m long and 50cm wide. The children participated in the experiments in pairs. First, a researcher showed them how the robot could be controlled by the sticks. Then, each child picked two sticks to use during the task. The sticks were always delivered to the children in the same order so that they could understand complementary concepts: one child was given the move-forward and stop sticks, and the other was given the turn-left and turn-right sticks. The children then practiced for one minute putting the foam shape close to the RFID reader and watching the robot move/stop/turn as the stick approached. Once they had been familiarized with the robot, a researcher explained the task to them. This consisted of guiding the robot from the beginning of the path to the spot where another Wall-E plush toy was placed, without leaving the path laid out. To make the task more entertaining, they were told that they had to help the electronic robot to reach its friend (the Wall-E plush toy) so they could play together. If the robot left the defined path, the educator stopped the game at the point where the robot exited the path.

Each group (pair of children) performed 4 repetitions of the task (2 repetitions of each path. An educator supervised and encouraged the kids while they were playing, while two researchers took notes on the children's behavior and impressions (e.g. the mistakes made in the interaction) and measured the time taken to complete the tasks.

9.4 Results

9.4.1 Success

The four trials carried out by each group were combined. If a group performed three or four tests successfully, they were considered capable of performing the tasks, otherwise they were considered incapable of doing so. The percentage of success in each task is shown in Table 9.1. The application of a one-way between-subject ANOVA with the independent variable *age group* and dependent variable *success rate* demonstrated that the *success rate* was significantly influenced by *age group* ($F_{3,42} = 23.871$, $p < 0.001$). The Bonferroni post-hoc tests revealed that only the success rate from the 2–3 age group was significantly different from the others. As can be seen in Table 9.1, this age group only got a 20% success rate, while the other groups got more than 90%.

9.4.2 Completion Time

The four trials carried out by each group were combined to perform the subsequent analysis. The average of each group's successful trials was used to obtain the average completion time value per group. If the trial was not performed successfully it was not included in the completion time analysis. The mean completion time of the

Table 9.1: Average (and standard deviation) measure for the success rate and the completion time in the tasks for each age.

Age (years)	Success (%)	Time (seconds)	Derailments (number)
2–3	20 (13.33)	150.63 (8.13)	7 (0)
3–4	91 (9.1)	125.05 (7.73)	4.30 (0.83)
4–5	100 (0)	139.48 (11.11)	3.55 (0.49)
5–6	100 (0)	99.05 (7.79)	2.91 (0.61)

task is shown in Table 9.1 by age group according to this combination. A one-way between-subjects ANOVA with the independent variable *age group* and the dependent variable *completion time* was conducted and the results demonstrated that *completion time* is significantly influenced by *age group* ($F_{3,33} = 4.217$, $p = 0.013$). The Bonferroni post-hoc tests revealed that children from the 5 to 6 age group performed the task significantly faster than the 4 to 5 group.

9.4.3 Accuracy

In order to evaluate how precisely the children were able to follow the path, the number of times in which the robot left the path (derailments) were counted (see Table 9.1). Even though the number of derailments was seen to decrease with age, the conducted one-way between-subjects ANOVA with the independent variable *age group* and the dependent variable *number of derailments* showed that it was not significantly affected by age ($F_{3,33} = 2.496$, $p = 0.079$).

9.4.4 Interaction Evaluation

In order to evaluate how children interacted with the robot, the errors during the interaction were split up into three categories. The first, *wrong stick* errors (E_{WS}), included the mistakes when children use an incorrect stick (e.g. turn right stick instead of turn left). The second, *wrong location* errors (E_{WL}), included the mistakes made when not putting the stick near the RFID sensor (on the Wall-E's "chest"). The *forced manipulation* errors (E_{FM}) included the situations when children try to use alternative ways (not using the designed sensor mechanism) to manipulate the robot (e.g. they use their hands/feet to turn/stop/move the robot). The average cumulative number of errors made in the four trials is shown in Table 9.2 by error type and age group. Since only two teams of the 2–3 year-old group completed the task successfully (and they used their hands to do so) this age group was excluded from the statistical analysis.

The ANOVA conducted with the dependent variable E_{FM} revealed that the number of times that children manipulated the robot by not using the sticks (E_{FM}) is not affected by the age factor ($F_{2,31} = 1.114$, $p = 0.342$).

Table 9.2: Average number of errors (and standard deviation) in the four trials by type (columns) and age (rows).

Age (years)	E_{WS}	E_{WL}	E_{FM}	**Total**
2–3	12 (6)	5 (5)	15 (1)	32 (2)
3–4	11.80 (1.07)	6.20 (1.28)	2.80 (1.20)	20.80 (1.91)
4–5	7.27 (1.23)	7.36 (1.30)	1.55 (0.59)	16.18 (2.22)
5–6	8.18 (1.33)	2.55 (0.51)	1.27 (0.30)	12 (1.82)

However, the ANOVAs conducted with the dependent variables E_{WS} ($F_{2,31} = 3.694$, $p = 0.037$) and E_{WL} ($F_{2,31} = 5.559$, $p = 0.009$) revealed that these errors were significantly influenced by age.

9.5 Discussion and Future Work

In response to the first research question (whether children are able to guide the robot along a predefined path) and according to the statistical analysis carried out, the research question is answered affirmatively for children aged three or older, since they were able to complete the tasks with success rates of around 100%. Hence, despite the complexity included in the experiment such as following a path and managing two different sticks, the children had the necessary cognitive skills to fulfill the tasks. In addition, the notes taken by the researchers showed that the older the children, the more the collaborative instructions they gave to each other to cooperate in the completion of the task. However, for the youngest age group the answer is negative, since only 2 groups of the 10 tested completed the task and did so mainly by guiding the robot with their hands instead of using the sticks. The children from the youngest age group got bored and apathetic when they made several mistakes by not using the right stick or putting it near the wrong part of the robot (not the RFID sensor) and hence felt that the robot was not acting as they wanted. The increased complexity of following a predefined path and having to manage two sticks (two different commands) was too difficult for them.

Evaluating the completion time, the statistical analysis revealed that the time spent performing the task is affected by age. According to the post-hoc tests and the data depicted in Table 9.1, there are no differences in the completion time used by the 3–4 and 4–5 age groups. However, the oldest age group (5 to 6 years old) performed the task significantly faster (40 seconds on average) than those aged 4 to 5 years.

Regarding the errors made by children when interacting with the robot, the statistical analysis showed that the total average number of errors decreases with age, which is an expected result related to more advanced cognitive and motor development. However, a more detailed analysis of the results reveals that errors associated with using the wrong stick are significantly higher in children under 4, but remain at similar levels in those between 4 and 6 years. This indicates that, despite children being more cognitively developed, they still have some difficulties when transforming the symbolic representation of a command (stick with different colors or shapes) into an actual action of the robot. Additional work would be needed to explore alternative ways of symbolically representing the commands and evaluating whether children are able to learn these forms of symbolic representation over time.

Regarding the wrong placement of the stick, the average number of errors remains at similar levels for children between 3 and 5 and that errors only occur occasionally after the age of 5. This indicates that by the age of 5 children have fully developed their cognitive skills to position a physical element (the stick) with high precision at a fixed point (the RFID reader). Finally, forced (stick-free) manipulations occur extensively with children less than 3 and nearly disappear in older children. This indicates that even at the age of 3 they internalize the proposed interaction method and use it as their natural way of communicating with the robot.

To sum up, the evaluation demonstrates that the proposed tangible-mediated robot is suitable for children aged 3 and older, since they are able to guide it in pairs and follow a defined path to move the robot to a specific location. However, the youngest children (2 to 3 year-olds) were not able to manage the complexity of manipulating two different sticks and following a set path. As future work, it would be interesting to use this robot platform to support educational and learning activities using the inherent ability of robots to gather several people around them simultaneously and support collaborative and cooperative actions.

Acknowledgments

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Chapter 10

Children's Acceptance of a Collaborative Problem Solving Game Based on Physical versus Digital Learning Spaces

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Abstract

Collaborative Problem Solving (CPS) is an essential soft skill that should be fostered from a young age. Research shows that a good way of teaching such skills is through video games, however the success of this method largely depends on the platform used. In this work we propose a gameful approach to CPS enhancement in the form of the CPSbot framework and describe a study involving eighty primary school children on user experience and acceptance of a game, Quizbot, using three different technological platforms: two digital (tabletop and handheld tablets) and another based on tangible interfaces and physical spaces. The results show that physical spaces proved to be more effective than the screen-based plat-

forms in several ways, as well as being considered more fun and easier to use by the children. Finally, we propose a set of design guidelines for future gameful CPS systems based on the observations made during this study.

10.1 Introduction

Problem Solving is one of many soft skills that a person may possess. Nowadays it is not enough for a student to simply have high grades, especially in engineering domains or in applied sciences; they are now also encouraged to have several other skills besides their technical knowledge, such as communication skills, teamwork, adaptability and problem solving, among others. Collaborative Problem Solving (CPS) emerges as a combination of several of these skills and is also highly valued and sought after. Vygotsky's Social Development Theory (1978) implies that a person's potential can only be achieved through interaction with and support from other, ideally more capable, people and various tools. This is based on the idea that when trying to solve a problem, the exchange of ideas could lead to a shared understanding that an individual cannot achieve alone. Gokhale (1995) also highlights the fact that "the active exchange of ideas within small groups not only increases interest among the participants but also promotes critical thinking." This leads to the conclusion that focusing on developing a person's individual problem solving skills is not enough and it is now essential to have a certain level of proficiency in collaborative problem solving.

Many methods can be used to nurture and enhance any given skill in children, including adding an element of play to the learning process, which has been proven to be a natural and successful way of improving the effectiveness of learning seeing as human culture is generated at least partially through play (Huizinga, 1949). With the aid of technology, educational games (or serious games) can be created to help develop skills like CPS through play and offer instant feedback and interactivity in a game-based learning environment. Educational games are designed to teach people about certain subjects, expand concepts, reinforce development, or help them learn or improve a skill (Dempsey et al., 1996) and they have been shown to have many cognitive, motivational, emotional and social benefits (Granic et al., 2014; Wouters et al., 2013).

Many technological games designed to foster CPS rely on digital tabletops, often considered adequate for collaborative learning activities because of their public display, which enhances workspace awareness (Gutwin and Greenberg, 1998, 2002) and in turn improves collaboration. These devices, however, are seldom used in actual educational settings, mostly due to their high cost or their form factor, which hinders their mobility. Handheld devices, on the other hand, are becoming more and more popular in these settings. However, their interaction is limited to touch contacts on the small screen area (Garcia-Sanjuan et al., 2016a). In contrast, others stand for tangible interactions, which have been identified suitable and interesting for designing learning activities for children (Strawhacker and Bers, 2014). Despite all of their different advantages, to our knowledge, no comparative studies have been made on which of these platforms is best accepted by children in the context of CPS learning. User acceptance is a key factor because, as has been shown in other technological and learning contexts (Bargshady et al., 2015; Pindeh et al., 2016; Tan et al., 2016), the usefulness, ease of use, and fun perceived by children influence their attitude towards the learning application usage and the effectiveness of the learning process.

In this context, the contributions of this work are manifold. First, the design of a framework (CPSbot), a gamified approach to teach CPS skills. Secondly, a study of a specific game (Quizbot) with eighty primary school students on three different technological platforms (a tabletop, tablets, and physical spaces). Our study reveals that physical spaces are perceived to be easier and more fun than screen-based sedentary activities, along with being the platform that subjects manifest as being the one they most want to use again both in class and out-of-class scenarios. Additionally, we consider how the framework can support CPS backed by observations made during the study, suggesting that physical spaces may provide more benefits for CPS enhancement than purely digital platforms, especially where planning and organization are concerned. Finally, we provide a list of guidelines for designers of future gamified CPS systems.

10.2 Related Works

Problem solving skills are highly valued and therefore there are many studies on nurturing and enhancing these skills. In this chapter we look at some of these works and separate them into different technologies.

10.2.1 Single-Display Multi-Touch Environments

The traditional desktop computer is a known and reliable medium very often used for educational games (Brayshaw and Gordon, 2016; Hatzilygeroudis et al., 2012; Liao and Shen, 2012; Raman et al., 2014; Siang and Radha Krishna Rao, 2003). However, studies show that younger children find it difficult to use a mouse and keyboard (Donker and Reitsma, 2007) and prefer newer multi-touch technologies (Romeo et al., 2003). Many studies showcase the benefits of using digital tabletops in education. These benefits include fostering creativity (Catala et al., 2012a), knowledge acquisition and transfer (Schubert et al., 2012), and, most importantly in this case, collaboration (Hornecker et al., 2008; Reski et al., 2014).

Works like the ones by Falloon and Khoo (2014); Martinez-Maldonado et al. (2015); Mercier et al. (2015); Waishiang et al. (2015) are examples of studies where single multi-touch displays were used to enhance Collaborative Problem Solving skills, among others. Mercier et al. (2015) test the effectiveness of the technology used by comparing the problem solving process on the multi-touch display with the usage of paper. The results of the work show higher levels of collaboration taking place when using multi-touch. The one by Falloon and Khoo (2014) is a more concrete study of the type of communication that takes place when an Apple iPad is used as a public workspace for a CPS class activity. The results show that indeed a lot of on-task talk took place, but it was necessary to include a teacher in order to help the students achieve the appropriate talk quality. Martinez-Maldonado et al. (2015) also present a classroom setting with teacher involvement that is composed of multiple interactive surfaces and aims to help teachers deploy and visualize their scripts in order to help idea generation during problem solving activities. Finally, Waishiang et al. (2015) introduce two interactive shared single display applications that use interactive patterns to facilitate effective communication among students during collaborative learning activities.

Unfortunately, tabletops are a rare commodity in real educational settings, mostly due to their high cost, as well as because of their form factor which prevents their usage in scenarios that require mobility. Other limiting factors associated with tabletops include the fact that the workspace is always public, making it difficult to perform any kind of private task, as well as the fact that the actual workspace dimensions are very limited and can only accommodate a certain number of participants (Garcia-Sanjuan et al., 2016b).

10.2.2 Multi-Display Multi-Touch Environments

One way of dealing with the disadvantages of tabletops while maintaining their positive aspects, such as awareness (Gutwin and Greenberg, 2002; Hornecker et al., 2008), parallelism (Rick et al., 2011), and fluidity of the interaction (Hornecker et al., 2008), is to use handheld tablets instead. Handheld tablets easily solve the public vs. private space issue by having a different tablet assigned to each person. Mobility is also increased with these devices due to their small size and light weight, and the workspace dimensions become virtually unlimited if the application is so designed. Furthermore, handhelds are now very common and can be found in any regular household due to their low cost, making it possible to follow a “Bring Your Own Device” (Ballagas et al., 2004) strategy if necessary.

There are several works that use tablets as multi-touch, multi-display platforms to either facilitate or enhance collaborative problem solving in an educational environment. Araujo et al. (2014), for example, use tablet PCs in a high school setting to encourage students to work collaboratively to solve mathematical problems. The results show a general improvement in the students’ grades after a semester of using the tablets in class. Similarly, Lohani et al. (2007) use tablets in individual and group problem solving activities in a freshman-year engineering course. Results show that the students liked using the tablets for taking notes and setting up collaborative sessions. The work by Sutterer and Sexton (2008) is another similar setup in a civil engineering course where the students used tablet PCs for collaborative note taking as well as collaborative problem solving. The study concludes that the students believed that both in-class and out-of-class learning were improved, however, the final test scores showed no significant changes in performance. Mayumi (2015) introduces two systems developed by Fujitsu and meant to be used with tablets. The first, called “Shu-Chu-Train,” improves the student’s ability to concentrate and retain information. The other, called “Manavication,” speeds up communication between the teacher and students while supporting the development of thinking power, judgment, and expressive power. The two solutions can be used to support the development of collaborative problem-solving abilities. Finally, Cheng-Yu Hung et al. (2014) and Hung et al. (2012) present a collaborative educational game consisting of a jigsaw puzzle that can be played on a Microsoft Surface. After performing a pre-game test and a post-game test on 20 participants (Hung et al., 2012) and 240 participants (Cheng-Yu Hung et al., 2014), the study concludes that the game did indeed help in raising the mean score in the tests.

Most of the works presented in this section include older participants of high school or college age. Furthermore, they do not try a gamification approach, instead opting for less engaging tool designs. Cheng-Yu Hung et al. (2014) and Hung et al. (2012) are the exception in that regard, but they fall into the same pattern as the rest by assuming that multi-touch tablets are the go-to solution and do not make any type of comparison with other platforms to test the effectiveness of these devices.

10.2.3 Tangible User Interfaces and Physical Spaces

When dealing with younger children (such as primary school students or even kids in kindergarten) Tangible User Interfaces (TUIs) might be an even more interesting platform than purely digital ones like tabletops and tablets. Works like the one by Strawhacker and Bers (2014) suggest that TUIs have an added value in early childhood education "as they resonate with traditional learning manipulatives." Studies such as the one by Schneider et al. (2011) have showcased the advantages of TUIs and Antle et al. (2009) even made a direct comparison between the traditional mouse-based setup and tangible interfaces in which it was observed that the latter enable more exploratory actions, which in turn provide faster and easier ways of interaction.

Tangible user interfaces offer the possibility of creating imaginative and original CPS activities like the ones presented by Schneider et al. (2012). Combinatorix combines tangible objects with an interactive tabletop to help students explore, solve and understand probability problems, which in turn allows them to develop an intuitive grasp of abstract concepts. The tool was only tested with five participants however and lacks a formal evaluation.

Several works which include a TUI platform focus on making a comparison with traditional methods and/or purely digital platforms, instead of presenting a tool on the TUI platform only. One example of such work is by Pan et al. (2015), who investigated the affordances and constraints or physical and virtual models integrated into a dynamics course. The students in this study were separated into three groups and received either traditional instruction, traditional plus physical manipulatives, or traditional plus virtual manipulatives. The results of the study suggest that adding physical and virtual manipulatives may be helpful. Schneider et al. (2011) also compare tangible and multitouch interfaces for collaborative learning and interaction, and conclude that tangibility helped perform the given problem solving task better and achieve a higher learning gain.

While these works do touch on CPS enhancement in some ways, they do not explore all the dimensions associated with the skill. For example, Pan et al. (2015) mention aiding communication, which we have identified as a CPS sub-skill, but completely overlook the planning process. Similarly, Schneider et al. (2012) focus on the collaborative aspect in general but not on the individual processes that make up CPS.

10.3 A Robot Board-Based Gamification Approach to Support CPS

For the purpose of this work, we developed a framework called CPSbot for multi-touch tabletops, handheld tablets, and physical spaces. CPSbot is, in essence, a framework for creating board games with a robot as the main actor that the players can move. Robots are a clear example of TUI and their usage in education has been steadily increasing. This is due to the fact that robots capture the imagination of children and therefore using them "to support teaching and learning ... has become a popular research topic" (Li et al., 2009). In addition, board games, particularly cooperative ones, are known to promote communication and socialization between the players due to their co-located nature promoting face-to-face communication (Eisenack, 2013; Zagal et al., 2006).

CPSbot aims to foster CPS by compelling the users to collaborate in order to solve the given problems. The platform enables the design of interactive exploration spaces where decision-making processes about the coordination of the actions to be carried out for the robot to follow a given path; the interactive elements to be consulted; the division of work or roles assigned to each participant, and the communication strategies to use take place continuously during the game as mechanisms that drive the acquisition of CPS skills.

10.3.1 Designing to Support CPS

The PISA 2012 problem solving framework identifies four cognitive processes in individual problem solving: exploring and understanding, representing and formulating, planning and executing, and monitoring and reflecting (OECD, 2010):

- *Exploring and understanding* implies understanding the situation by deciphering the initial information provided about the problem and any further information that appears during the exploration of and interaction with the problem.

- During the *representing and formulating* process, the information gathered previously is selected, organized, and integrated with previous knowledge. This is achieved by representing the information in the most convenient way, whether using graphs, tables, symbols, or words, and then formulating hypotheses by extracting the relevant factors and evaluating the information.

- *Planning and executing* includes clarifying the goal of the problem, setting sub-goals, and developing a plan to reach the main goal. The plan created in the first half of this process is then executed in the second part.
- Finally, *monitoring and reflecting* implies monitoring the steps in the plan to reach the main goal and reflecting on any possible solutions and assumptions.

Problem-solving tasks can be categorized by one or several of the following properties: large, complex, spatially distributed, and in need of extensive communication and a large degree of functional specialization between the agents (Obeid and Moubaiddin, 2009). If a problem satisfies one or more of these properties it is considered to be unsolvable by a single agent and therefore the collaboration of several agents is required. The PISA 2015 (OECD, 2013) definition of Collaborative Problem Solving competency is "the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills, and efforts to reach that solution." From this definition we can extract three core competencies, which are:

- Establishing and maintaining shared understanding
- Taking appropriate action to solve the problem
- Establishing and maintaining team organization

CPSbot has been designed to support the previous CPS processes and competencies. More specifically, its design revolves around the following four sub-skills associated with CPS (OECD, 2013):

- *Negotiation*: wherein the agents involved in the CPS task are expected to share their knowledge, express their ideas and come to a shared understanding leading to an agreement over the solution of the problem or the course of action to take in order to reach a solution. In some cases, an actor is expected to learn to become more flexible in the negotiations, while in other cases an actor may need to learn to be more assertive.
- *Planning*: this includes the ability to divide a given problem into smaller tasks and formulating as efficient a plan as possible in order to reach the final solution.
- *Communication*: this is the skill that makes the enhancement of the other skills possible. Negotiation, planning and organization can only be achieved through communication; therefore, it is essential to develop the right type of communication in order to ensure the correct transmission of information and the effective interaction between the actors.

- *Organization*: wherein the agents are expected to take on the necessary roles in the team in order to structure and coordinate their efforts and therefore reach a solution in the least chaotic way possible.

According to the previous specifications, three main design aspects of CPSbot would make it suitable to support CPS: the distribution of game elements on a publicly visible and accessible board, the distribution of the robot's movement commands among the players, and the slow pace at which the game is played. With respect to the former, the fact that all items are *spatially distributed* on the board and made available to every player would enable *exploring* the possible solutions, *planning* the proper path for the robot to take, maintain a *shared understanding* of the game state and the resolution process, and, once a solution is *executed* (i.e., bringing the robot to a specific cell), *monitoring* the decision adopted. In turn, the distribution of the movement commands would enable the *functional specialization* of each participant, making team *organization* through *communication* necessary not only to move the robot, but also to be able to solve the game problems correctly. The choice of having a slowly-paced action is also important, since it would allow the users to take their time to *understand* the problem statement presented, *negotiate* and *plan* a strategy, and finally, in case of failure, *reflect* and propose another one. Of course, the educational contents in the form of problems being defined by teachers would be crucial to fully and successfully develop CPS skills. Therefore, teachers will be provided with a tool to specify those contents.

10.3.2 Quizbot: A CPSbot Game

Gamification, or gameful design, is defined by Deterding et al. (2011) as "the use of design elements characteristic for games in non-game contexts." Therefore, when designing a specific game with CPSbot, we took the five game dynamics identified by Bartel et al. (2015) in accordance with Deterding et al.'s definition into consideration. These dynamics are constraints, emotions, narrative, progression, and relationships.

Among the different game approaches that could be implemented with CPSbot, a quiz-style board game was selected because, as pointed out by Harris (2009), in this type of game students "participate and collaborate as members of a social and intellectual network of learners and . . . the learning takes place as a natural and authentic part of playing these board games". This is also confirmed by Westergaard (2009) who points out that quiz-style games "can encourage participation and foster an informal, positive and energetic learning environment". Finally, this is an effective learning strategy because it supports retrieval practice which is, as pointed out by Blunt and Karpicke (2014) "a powerful way to enhance long-term meaningful learning of educationally relevant content".

Following this design strategy, the CPSbot framework was used to implement Quizbot, a robot-based board, quiz-style game (see Figure 10.1). In Quizbot the players are presented with a board split up into an undetermined number of cells.

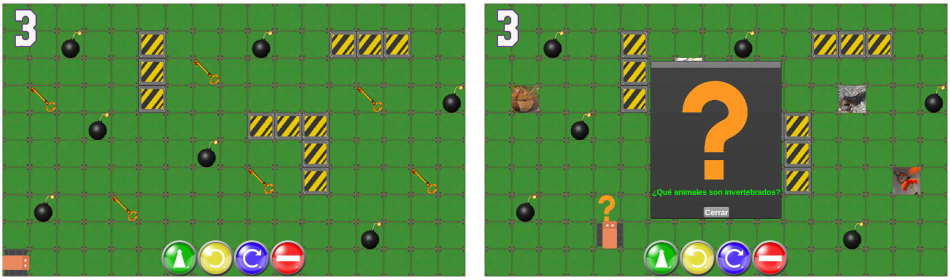

Figure 10.1: Quizbot in normal mode (left) and quiz mode (right).

At this point the game is considered to be in its normal mode (versus the quiz mode described further below). The board cells may be empty, or they may contain one of the following items:

- *Key*: this is the most important item in the game. Keys are used to activate the game's quiz mode, which presents the players with a question that must then be answered.
- *Block*: this is a mostly harmless item that simply serves as a blockade. These cells cannot be passed through by the robot that the player controls on the board.
- *Bomb*: this could be considered the game's main antagonist. Colliding with a bomb while the game is in quiz mode undoes any previously correct answers and the quiz is restarted from the beginning.

The bombs in this case work both as the main *constraint* in the game when considering the previously mentioned game dynamics, as well as for interaction precision measurement. They are also meant to be the main cause of *emotional* outbursts in players (whether negative due to collision or positive due to evasion).

The board itself also contains a robot which acts as the player's agent. Four movement commands are associated with the robot and players may have any number of these commands available to them. The commands are: go forward, turn left, turn right and stop. The reason behind this setup is so that in a multiplayer case, different players would control different commands and must coordinate with each other in order to move the robot efficiently, thus fulfilling the *relationships* metric in the gameful design. In the normal mode, the goal is to move the robot to a key-containing cell while avoiding blocks and bombs in order to activate the next quiz. Once that is done, the game enters into quiz mode.

In quiz mode, the blocks and bombs remain in place but all the key-containing cells minus the one that the robot reached in order to activate the quiz are turned into answer cells. The reached cell is turned into a question cell instead. A question cell, as the name suggests, contains a question that the player(s) must answer. A question, or quiz, is answered by guiding the robot to the correct answer cells. The game contains three types of questions that must be answered in different ways:

- *Choice questions*: this type of question is basically a multiple choice type of question where the players are presented with several answers and must choose the correct one(s) out of those, visiting the cells containing these answers in any order of the players' choice.
- *Ordering questions*: in this type of question, all the answers are correct but the cells containing them must be visited in a specific order dictated by the question itself.
- *Accumulation questions*: these questions provide the players with a greater freedom of choice where answering is concerned. The players simply have to choose any number of answers wherein their sum equals the value given in the question.

Once a question is answered correctly, the quiz is considered ended and in the case of there being more questions available the game goes back to its normal mode with the previous keys (or answer cells), bombs and blocks being removed from the board and replaced with new ones scattered over different cells. If there are no further questions available, the game is considered to have finished. The number of questions in the game and the distribution of the items per question on the game board can be modified using an external application (see Figure 10.2), which creates and stores configuration files that Quizbot accesses on startup, making it possible to follow any desired game *narrative*. *Progression* can also be achieved through this by increasing the difficulty of the question or increasing the number of bombs (or constraints). The number at the top left corner of the board would serve as an indicator for this progress.

Quizbot for Tabletops and Handheld Tablets

Quizbot is based on a client-server architecture, where the tabletop or the handhelds would act as clients, making it possible to have the same game view on more than one device at a time. This way, each user could have their own private space while still seeing the game board with the results of the actions taken by everyone playing. While this is not particularly interesting for the tabletop platform, shown in Figure 10.3, it is so for the handheld tablets, shown in Figure 10.4 (where, in this particular case, each tablet has one of the four possible movement commands).

Quizbot for Physical Spaces

Introducing physical spaces into traditionally sedentary games is a practice that is becoming increasingly popular. Physical body movements are proven to be essential for the enjoyment of life (Bowlby, 1969) and several works highlight the benefits of games which favor physical activity and make use of tangible objects (Cheok et al., 2005; Xie et al., 2008). Therefore, we created a version of Quizbot

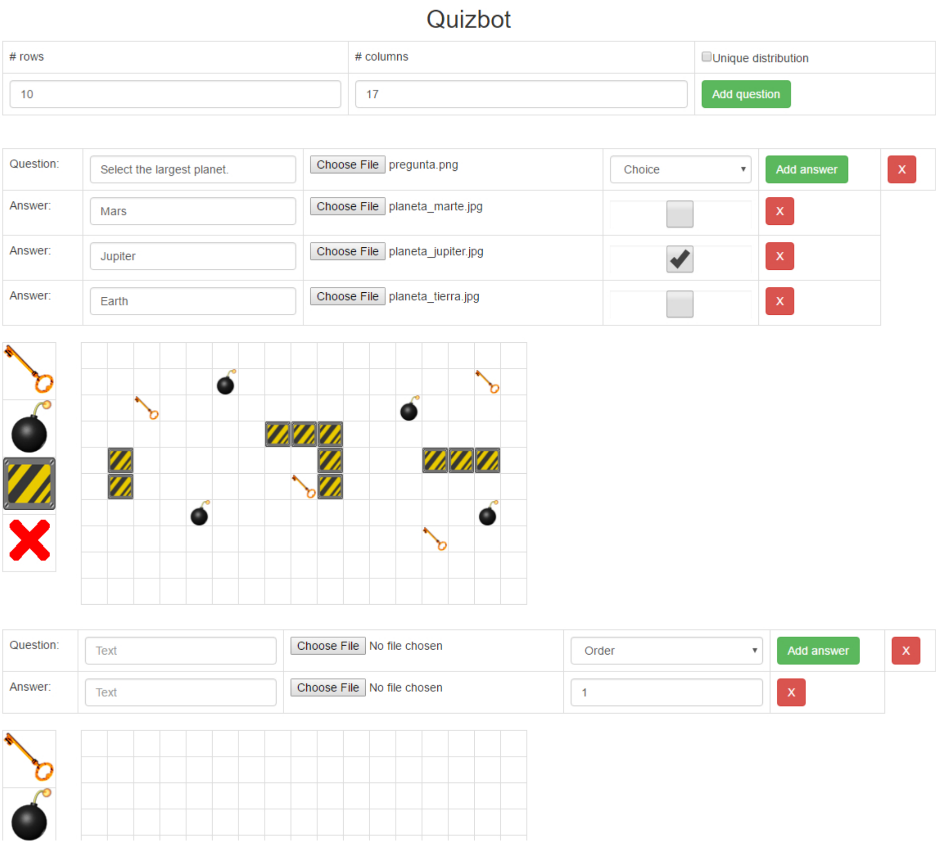

Figure 10.2: Quizbot configuration application.

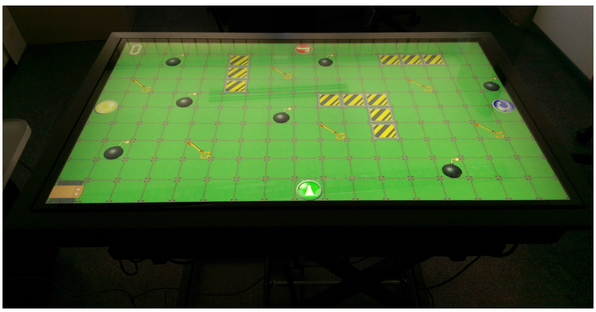

Figure 10.3: Instance of Quizbot running on a Windows Tabletop.

Figure 10.4: Four connected instances of Quizbot running on Android Tablets.

using a mixture of physical and digital spaces for a Tangible User Interface experience.

For this platform, several objects and devices were used to create Quizbot (Figure 10.5). The non-technological objects included interlocking foam mats for a 7m × 4m board, where each piece of the mattress represented a cell on the board. Foam tubes were used to represent "block items", and inflatable rubber balls were used to represent the "bombs" on the board. As for the technological aspect of the game, several Android handheld tablets were used as "key cells" to be placed on the foam mattress in their corresponding cell. Furthermore, a Lego Mindstorms robot (Figure 10.6) was used as the actual robot actor to be controlled on the board. Finally, in order to allow for communication between the board and the robot, RFID tags were placed around the "key" and the "bomb" cells on the back side of the mattress, and an Android phone connected to an RFID reader was mounted on the robot. This communication is made through the game server, where once a tag is read, the smartphone sends a message to the server about whether it was a key or a bomb cell (in case of the former, the ID of the cell is included), and the server then behaves according to the message received.

10.4 Evaluation

The overall goal of our study was to analyze the experience of primary school children with a game-oriented approach based on physical spaces for the enhancement of CPS skills and compare the proposed gamification approach with other more traditional technologies based on tabletops and multi-touch tablets.

10.4.1 Participants

Eighty primary school students between the ages of 9 and 10 took part in the study, of which 36 were girls and 44 were boys. The study was carried out at the Universitat Politècnica de València's Summer School, with the additional benefit of the children being from different schools with different curriculums.

Figure 10.5: Quizbot in a physical space.

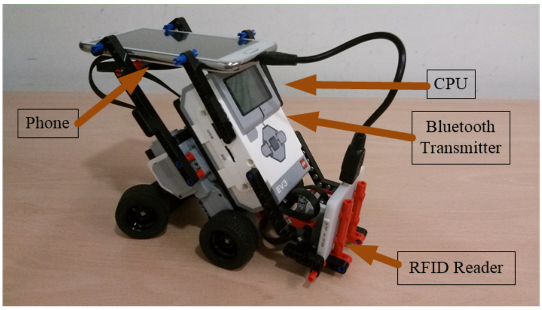

Figure 10.6: Tangible Lego Mindstorms robot setup.

10.4.2 Apparatus

Two implementations of the game were made. A version for the tabletop and handheld tablets was implemented using the LibGDX framework and Node.js. The tabletop device used ran Windows OS and included a 42-inch multi-touch screen. The tablets for the handheld version were BQ tablets running Android OS. Finally, the tangible version of the game was developed in native Android. RFID tags and an RFID reader were used to identify "bomb" and "key" item cells. An Android smartphone connected to the RFID reader was mounted on a Lego Mindstorms robot, allowing it to also read movement commands from RFID tagged paddles. BQ tablets running Android OS were used to simulate "key" item cells showing the quiz questions and answers.

10.4.3 Procedure

The children were separated randomly into 10 groups of 8 and were made to test the three platforms in different rotations. For example, one group would start with the tabletop then move onto the handheld tablets and then onto the TUI, while another group would start with the TUI platform then move onto the tabletop and then onto the handheld tablets. This ensured that the order in which a platform is tested does not affect factors such as enjoyment or learning. The questions to resolve on the platforms were also rotated in order to ensure that any possible variability in problem difficulty would not have an effect on the children's impression of the platform. The questions themselves were taken from third and fourth grade school textbooks.

For each group on each platform, four children were playing at any given moment while the other four would observe from the sidelines. They would then switch after three minutes of gameplay and then back again after another three and so on, for a total of 18 minutes of gameplay. This does not include the time it took for them to complete a trial question at the beginning of each platform's session. Each participant was given control over one of the robot's commands (turn left, turn right, move forward, stop) and they were left to their own devices as far as everything else was concerned. Throughout all the activities, several observations were made of the children's behavior. Furthermore, at the end of each group session, after a group had tried out Quizbot on all three platforms, a questionnaire was passed out to each child in order to get their feedback on the experience. The questionnaire itself is a Fun Toolkit (Read, 2008; Read and MacFarlane, 2006) questionnaire adapted to this study. Table 10.1 shows the questions that were asked in the questionnaire. Questions 1 to 6 use a Smileyometer in order to measure how much fun the children had on each platform and how easy they found controlling the robot was on each platform. Questions 7 to 10 use a Fun Sorter in order to measure on which platform the children thought they performed better and worse, and on which platform the children had the most and the least fun. Questions 11 and 13 use an Again-Again table where the children can report the likelihood with which they might play the game on each platform inside and out-

Table 10.1: Post-game session questionnaire.

#	**Question**
1	How much fun did you have with the game on the floor?
2	How much fun did you have with the game on the tablets?
3	How much fun did you have with the game on the big table?
4	How easy was it to handle the robot on the floor?
5	How easy was it to handle the robot on the tablets?
6	How easy was it to handle the robot on the big table?
7	With which version do you think you did best?
8	With which version do you think you did worst?
9	With which version did you have the most fun?
10	With which version did you have the least fun?
11	Would you like to play again in class?
12	In what subjects would you play?
13	Would you like to play again outside class?
14	Would you prefer to play alone or with friends?
15	What would you change in the game to like it better?

side a classroom. Finally, questions 12, 14 and 15 are additional, Quizbot-specific questions in order to have a better grasp of the type of quiz questions the children prefer, and whether they prefer playing in collaboration with friends or whether they prefer playing alone. The last question is simply for future reference, in order to make Quizbot more appealing and therefore possibly more effective.

10.4.4 Results

This section describes the three types of result obtained from the tests: performance results obtained from the game logs, user impressions from the questionnaires that all the participants filled out, and a summary of the observations we made during the session.

Performance

The three platforms included a logging system, each of which logged events such as the movement command given, a bomb contact, an answer has been reached, a quiz has started, and a quiz has ended. Table 10.2 shows a summary of the averages per platform obtained from these logs as well as the significance level obtained from running a Friedman test on them. With $\alpha = 0.05$, the only significant differences found were for the time between answers and the number of wrong answers. A Wilcoxon test was then used to check for significant differences between pairs of platforms for the two significantly different variables. The results of a Bonferroni adjustment ($\alpha = sfrac0.053 = 0.017$), which takes into consideration that three independent variables are being compared, indicate that the significant differences

Table 10.2: Log summary.

Variable	**Tabletop**	**Tablets**	**TUI**	p
Commands given	344.571	375.333	271.583	0.205
Bomb contacts	2.429	2.333	3.333	0.341
Wrong answers	8.571	9.167	1.583	0.000
Quizzes completed	1.571	2.333	2.083	0.201
Time between answers (sec)	46.091	40.648	83.223	0.001
Time between correct answers (sec)	72.386	86.828	80.894	0.368
Time to finish quiz (sec)	212.667	238.158	224.536	0.197

Table 10.3: Wilcoxon test results for platform pairs.

Variable	**Platform 1**	**Platform 2**	p
Wrong answers	Tabletop	Tablets	0.637
Wrong answers	Tabletop	TUI	0.002
Wrong answers	Tablets	TUI	0.004
Time between answers	Tabletop	Tablets	0.182
Time between answers	Tabletop	TUI	0.005
Time between answers	Tablets	TUI	0.002

are in the comparisons between the tangible platform and the other two platforms for both the average number of wrong answers and the average time between answers (Table 10.3).

Impressions

The results obtained from the Fun Toolkit questionnaire are reported in this section. The questions were split into groups where the same factor was being measured for the different platforms in order to see how the children perceived the platforms.

A Wilcoxon test was used on the Smileyometer results in which the questions were paired by platform (tabletop, tablets, tangible) for each measurement factor (fun, ease of use). The results of these tests are summarized in Table 10.4, where it can be seen that the only statistically significant difference ($p < 0.017$, due to the Bonferroni adjustment) obtained was between the tablets and TUI *ease of use* factor.

The results from the Fun Sorters where the children's platform preferences for the fun and the ease of use factors were asked explicitly (questions 7 to 10) are shown in Table 10.5. The average score is shown for each platform. This score was established by assigning 3 points to the platform that was chosen as the best, 2 points for the platform that was chosen as second best, and 1 point to the platform that was chosen as worst. This means that the closer the score is to 3, the better

Table 10.4: Smileyometer result comparison (questions 1 to 6).

Variable	Platform 1	Platform 2	p
Fun (Q1-3)	Tabletop	Tablets	0.461
Fun (Q1-3)	Tabletop	TUI	0.06
Fun (Q1-3)	Tablets	TUI	0.019
Ease of use (Q4-6)	Tabletop	Tablets	0.02
Ease of use (Q4-6)	Tabletop	TUI	0.438
Ease of use (Q4-6)	Tablets	TUI	0.005

Table 10.5: Fun Sorter results. Mean score for each platform is shown between parenthesis.

Variable	Best	Intermediate	Worst
Easy to use	TUI (2.45)	Tabletop (1.86)	Tablets (1.74)
Fun	TUI (2.64)	Tabletop (1.96)	Tablets (1.47)

it is. Table 10.6 shows the results of the Wilcoxon test applied to the results of the Fun Sorters.

Figure 10.7 shows the results of the Again-Again tables in which the children state their intention of playing again on each platform in class and outside (questions 11 and 13). The general response in both cases can be seen as a positive one. Table 10.7 displays the results of the Wilcoxon test applied to the Again-Again tables and shows that, while all three platforms got a generally positive reply, the tangible platform got a significantly more positive reaction in comparison. Figure 10.8 shows which school subjects the children prefer for the quiz questions on each platform (question 12).

Figure 10.9 shows the ratio of children who prefer playing alone vs. with friends on each platform (question 14). The majority of them stated that they would rather play with friends on all three platforms. Finally, Figure 10.10 shows

Table 10.6: Fun Sorter results comparison (questions 7-10).

Variable	Platform 1	Platform 2	p
Ease of use	Tabletop	Tablets	0.445
Ease of use	Tabletop	TUI	0.000
Ease of use	Tablets	TUI	0.000
Fun	Tabletop	Tablets	0.000
Fun	Tabletop	TUI	0.000
Fun	Tablets	TUI	0.000

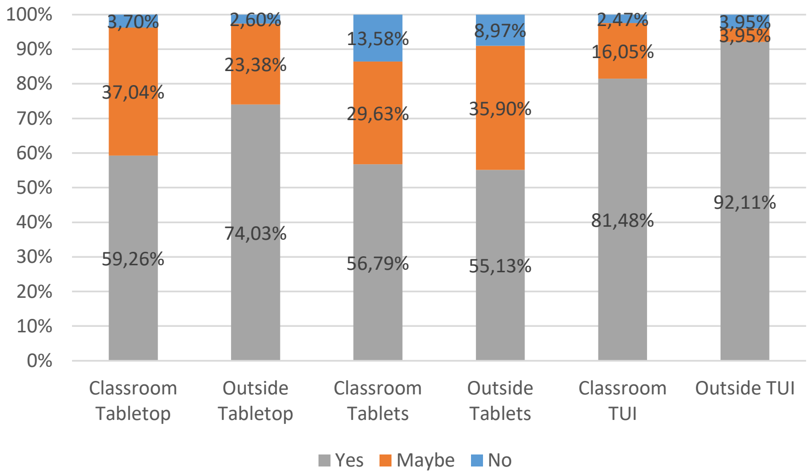

Figure 10.7: Again-Again table results, stating desire to play again in class and outside.

Table 10.7: Again-Again tables results comparison (questions 11 and 13).

Variable	Platform 1	Platform 2	p
Classroom	Tabletop	Tablets	0.148
Classroom	Tabletop	TUI	0.004
Classroom	Tablets	TUI	0.000
Outside	Tabletop	Tablets	0.648
Outside	Tabletop	TUI	0.088
Outside	Tablets	TUI	0.001

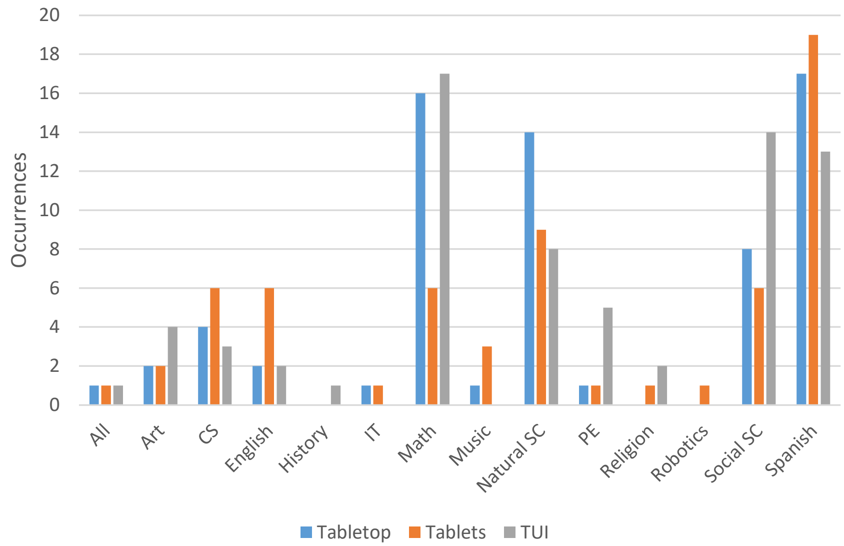

Figure 10.8: Results for which school subjects are preferred for questions on the three platforms.

some of the changes that the children suggested for Quizbot (question 15). Most of these changes appear to be related to the game visuals.

Observations

Throughout the game sessions, several observations were made of the children's general behavior with respect to CPS and some patterns were extracted from these observations.

The most frequently observed action on all three platforms was planning. Whether it was at the beginning of each quiz or after a correct (and sometimes incorrect) answer, the children would stop and discuss which path to take to get to the next question. Some of the discussion revolved around whether the robot would be able to pass between two items on the board or not. Sometimes, they would plan ahead for several answers. However, there were also some cases in which no plans were made and a couple of children would take charge and try different answers randomly. It was not only the children who were playing at the moment who planned; the four children watching from the sidelines were also observed planning in hushed voices for when it was their turn to play.

Another frequently observed action was exploration. Whenever a new quiz would start, the children would check out all the answers before starting the planning process. This was observed most frequently on the TUI platform, especially among the children watching from the sidelines. During the exploration and plan-

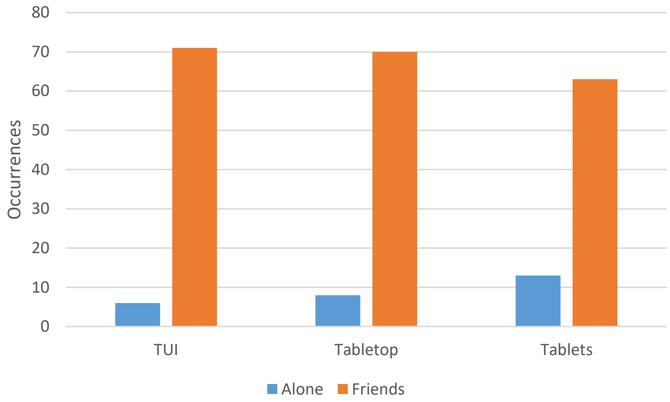

Figure 10.9: Company preference for three platforms.

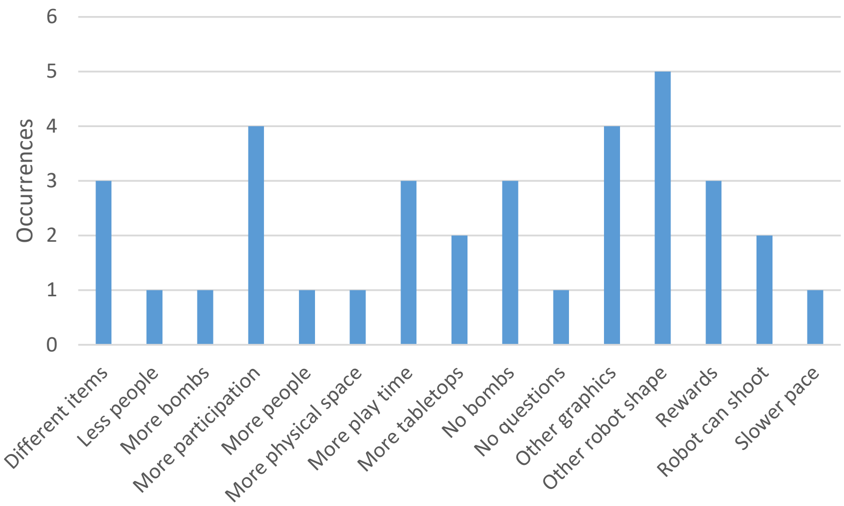

Figure 10.10: Changes suggested for Quizbot.

ning processes, a lot of knowledge sharing also took place, especially if a child was sure of an answer or if someone asked a question.

A lot of negotiation in different forms took place on all three platforms. For example, sometimes the children would discuss whether a set of answers was correct or not and would then agree to check one answer out and then another. Negotiations related to path planning also took place, where they would evaluate whether it was worth risking a shorter path containing bombs or if it was better to play it safe and take a longer path. Some subgroups would also negotiate which movement command each person would have whenever it was their turn to play. This last type of negotiation was observed most frequently on the TUI platform and sometimes on the tablet platform, but rarely on the tabletop.

In most groups, one of the children would eventually take on a leadership role, ordering movements constantly. Most of the children would shout for the robot to be stopped, especially when it was about to collide with a bomb, making some children either avoid having that movement command or purposely ask for it, but the group leaders would shout out all the movements, telling the others when to go forward or when to turn.

In some groups, children would get fed up with waiting for someone to perform a movement command and would either invade the other's workspace (in the tabletop and tablets case) or grasp the other child's hand to force them to perform the wanted command.

In some groups, the children waiting on the sidelines would collaborate with those currently playing by telling them the answer or warning them about a bomb. This occurred most frequently on the handhelds platform, but also sometimes on the other two platforms. However, the children on the sidelines were more frequently found trying to annoy those playing by counting down the time for their turn to end, taunting them, asking for them to collide with a bomb or to choose a wrong answer, giving them wrong answers, or actually sabotaging by invading their interface.

There were also cases where one of the players would sabotage the rest by constantly turning the robot or stopping it as soon as it started moving. In these cases, the other children would either tell them off or, in a few cases, physically stop them by grabbing their hand.

Overall, there were several groups with good coordination and groups with bad coordination. Sometimes a person would know and say the correct answer but the others would ignore them, causing them to sulk and ignore the game. In some cases, after answering wrongly, part of the group would sulk and momentarily stop playing. There were also cases where someone would try to cheer up the rest of the group and encourage them to try another answer.

As far as individual platform observations go, a couple of children complained about the warm air given off by the tabletop, as well as about having to read the question and the answers upside down (for those standing in the north position). In the latter case, the person standing in the south position would help by reading the text out loud.

While playing on the tablets platform, the children would sometimes stand up when they got excited (such as when they answer something correctly or, in the case of the children on the sidelines, a wrong answer is chosen). The children on the sidelines would also stand up sometimes to have a better view of all the tablets, even though they can view one or two tablets easily from their position. A lack of coordination was also observed when it came to the two children with the turning movements; they would often turn the robot left and right at the same time, causing it to stay in the same position. They would also often call out an answer to go to, by saying "This one!" while pointing at their own tablet, causing the others to ask "Which one?" in return.

Finally, when faced with the TUI platform, several children would make satisfied exclamations such as "That's so cool!" or "This is great!" and so on. In a few cases, the children would make the robot purposely collide with the blocks. There were also cases where the robot came apart because of the children's rough handling (whether because of colliding or because they moved the robot manually). On some occasions, the children who were supposed to be on the sidelines would stay on the board to observe the actions of those who were playing, while on others they would move around the board to play with the foam blocks or the rubber balls.

10.4.5 Discussion

Performance

The performance results show an overall lack of significant differences between the three platforms, which is interesting in certain cases, such as in the number of quizzes completed. We expected fewer questions to be completed on the platform using physical spaces due to the bigger size of the board making it more time consuming to check the different answers, but the groups divided that task efficiently enough between the members to make this not be the case. Instead, the bigger board size could be the reason behind the two significant differences that were obtained from the logs. We observed the children colliding with an unwanted (and usually incorrect) answer by accident several times on both digital platforms (usually when trying to make a right or left turn), making the average time between answers in general less than on the tangible platform despite the average time between correct answers being mostly similar. This could be due to the perceived distances on the board; the bigger physical board amplifies the otherwise small distance that is seen on a screen. The children would shrug off the accidental collisions with wrong answers the same way they would shrug off a collision with a "block" item, which is probably why these collisions had no effect on the total time it would take them to complete a quiz.

Overall, these results seem to indicate that the platform using physical spaces is the best platform to use with children. The two variables with significant differences (number of wrong answers and time between answers) are both affected by movement precision, and unlike screen-based technologies, where size is either limited or hard to extend, physical spaces make it very easy to expand the game world, therefore assisting with tasks that require a certain amount of precision. On the other hand, as far as the rest of the measured variables are concerned, the three platforms provided no significant differences, meaning that no single platform provides any particular disadvantage, while physical spaces do provide a major advantage.

Impressions

The main purpose of the Fun Toolkit questionnaires was to compare the three platforms in order to see whether one would stand out from the rest. Overall, it seemed like the children's preference was the TUI platform using physical spaces.

The Smileyometer results (questions 1 to 6) showed that the tangible interface was easier to use than the tabletop/tablets, and this agrees with the Fun Sorter results shown in Table 10.5 and Table 10.6. This could be due to a combination of smaller public workspace in the latter, which makes knowledge sharing harder, and the generally higher difficulty observed with the entirely digital version of the game. Table 10.5 and Table 10.6 show that the tangible platform was both the most fun and the easiest to use, while the tablets were both the least fun and the least easy to use, which suggests a correlation between the two variables. The reason behind these results could be that the TUI was more intuitive for the children, as some previous studies revealed (Schneider et al., 2011; Strawhacker and Bers, 2014). The tangible game being a generally rarer type of activity might also affect the fun factor in this case.

The results of the Again-Again table (Figure 10.7) show a mostly positive reaction to all three platforms, which could possibly be related to the children's age and their eagerness to play most of the time. This could be considered a positive result since the intention is to make CPS skill enhancement fun so that the activity would be repeated willingly, thus helping to further enhance the children's Collaborative Problem Solving skills.

Figure 10.8, which displays what subjects the children would like to study using the three platforms, does not show much variety between the subjects the children chose based on platform, but there is somewhat more of a variety of subjects on the TUI platform. This could be due to the wider options this platform provides. For example, Physical Education-related activities would be harder on the digital-only platform.

When asked whether they would rather play Quizbot alone or with friends, an overwhelming number responded that they would prefer to play with friends. This is a positive result considering the purpose of Quizbot is to enhance Collaborative Problem Solving, which requires the participation of more than one agent. The handheld tablets might have the highest number of replies indicating they would rather play alone due to children perceiving tablets as generally private devices.

On the last question in the questionnaire, where the children were asked about any changes they would make to Quizbot, it can be noted that most of the changes suggested by the children are aesthetic, suggesting that visually pleasant items are more appealing, which is important to take into consideration when creating something with the intention of being used repeatedly. Some children also wanted higher participation from the other children in their group, possibly indicating a difference in motivation levels. This would probably be avoided in cases where friends were playing together during a time they chose themselves. Finally, an interesting change that was suggested is one related to receiving rewards, which is a common extrinsic motivator in games. While an interesting addition to consider, studies suggest that it is more rewarding for the learning process to rely on intrinsic motivation instead (Deci et al., 1991; Werbach and Hunter, 2012).

Observations

As for the observations that were made during the study, a lot of them involved seeing communication, negotiation, and planning taking place, which is in accordance with the processes needed for CPS to be fostered (OECD, 2013). Organization varied between the different teams, mostly depending on whether there were one or two children sabotaging the activity or not, which could be attributed to children simply acting their age. Sometimes, better organization simply took longer, waiting instead for a group leader to appear. Other roles identified by Fan (2010) as usually formed during a CPS activity were also present to different degrees in each group. These roles are Brainstormer, Critic, Supporter, and Team Wrangler.

The three main CPS competencies discussed in Section 3.1 were clearly observed taking place during the study. The children would share their knowledge when required, take action to solve the given questions and maintain some level of organization. The fact that improvement in some of these aspects could be observed already shows that Quizbot fulfills its intended purpose of encouraging the practice of the CPS sub-skills and CPS skills in general.

On a platform-specific level, the reason more exploring took place on the TUI platform could be the fact that the children had to move around to explore, and that is precisely what the children wanted. It would also explain the constant standing up on the other platforms. More negotiation was observed on the TUI platform as well, at least when it came to negotiating what movement command (which could be considered a tool) each child would have. Since this was observed on the handhelds as well, albeit to a lesser extent, it could be related to the fact that it is easier to move the movement commands around on these two platforms. The only drawback that we found on the TUI platform was that it was somewhat distracting for the children, diverting them from the game's main objective while they sometimes walked around the board aimlessly.

The tabletop platform's main flaw was having to read text upside in some positions, which could be attributed to its limited workspace dimensions. As a possible solution, 360º controls could be used to enable all users to have the same view, regardless of their position (Catala et al., 2012b).

Finally, the handheld tablets provided a mixed bag of results. On the one hand, the private space seemed to have made coordination more difficult for the children because they would point at their own tablet and say "here" or "there" when referring to a point on the board to go to. However, this can be seen as an opportunity to improve the children's communication skills by encouraging them to be more specific and descriptive with their language.

Design Guidelines for Future Game-Based CPS Systems

As a result of this work, we have come up with a series of recommendations for future Game-based CPS designers. These lessons are based mostly on our observational results, but also take into consideration the results on performance and user impressions.

1. *Design to Support Discussion*: While one of the main CPS sub-skills is communication, it is important to design the system so that it would support discussion through communication, rather than only require straightforward or one-way communication.

2. *Design to Support Types of Negotiation*: Just as with communication, negotiation comes in various forms. Design a system that supports negotiation for both the actual work as well as for the tools available.

3. *Design to Support Levels of Planning*: Design to allow incremental amounts of pre-planning. Planning further ahead should be more rewarding, but wasting too much time on planning should be penalized.

4. *Design to Include Different Roles*: Design an environment where typical CPS roles (Brainstormer, Critic, Supporter, and Team Wrangler) can emerge naturally. The different roles help with developing innate organization.

5. *Design to Support Private vs. Public Spaces*: Separately, each type of space has its own advantages and disadvantages, but having a public-only space is not usually representative of a real workspace, while a private-only space makes discussion and knowledge sharing harder. Therefore, an ideal setup would be a mixture of the two.

6. *Design for Intrinsic Motivation*: Design to elicit intrinsic motivation rather than using only extrinsic motivators. The users' wants can sometimes clash with their needs, therefore designing intrinsic motivators may be more reliable.

10.5 Conclusions

This work focuses on the many soft skills that are required of today's students, and the consolidation of said skills into what is referred to as Collaborative Problem Solving. These skills can be nurtured and enhanced in many ways, but one way that has been proven to be effective for learning in general is through video games. However, the program's effectiveness mainly depends on the platform used.

Reviewing other works that are related to the subject at hand revealed that, while it is generally agreed upon that collaborative problem solving skills need to be developed in all students, very few try to add a gamification approach to the enhancement process. Comparisons between platforms to test the differences that they could provide besides the tool itself are also rare. A CPS skills enhancement framework called CPSbot and a quiz-style game based on this platform, Quizbot, was therefore developed on three platforms in order to compare user experience and acceptance of an approach using physical spaces with screen-based sedentary platforms.

Quizbot is a mixture of a board game and a quiz-solving game, where the users control a robot, moving it on a board with cells containing different game items. Some game items trigger quizzes that the players must answer, also by guiding the robot to the correct answer(s). The game presents a CPS scenario by urging the players to coordinate their actions to make the robot move, plan the robot's route and share their knowledge to answer the quiz questions.

The first of the three platforms Quizbot was developed for is a multi-tactile tabletop, which provides a public space where players can share their knowledge with more ease. The second is a multi-tactile handheld platform where the board can be viewed on several tablets, making it possible to give each player their own private space. The third and last platform is based on a Tangible User Interface using physical spaces where the robot, the game board, and even the robot movement commands became physical objects.

A study was performed with eighty summer school students in which the they were split into groups of eight to try out the three platforms in turn. The children were observed without interference while they played, and at the end of each group session, a questionnaire was handed out. A summary of the logs taken by the logging system that was previously implemented shows that the only significant gameplay differences between the platforms were in the number of wrong answers and the time between answers, which can probably be attributed to the perceived distances due to the board size. The questionnaire itself showed that the TUI platform was both the most fun and the easiest to use, besides the fact that it instilled a general eagerness to play again both in class and out-of-class environments. The observational results of the study provided feedback on concrete differences between the three platforms, as well as verifying that Quizbot serves its intended purpose and encourages the use of the skills associated with CPS. Finally, this study provides the first evidence that indicates that, despite the current widespread individual tablet-based learning strategies, educational technology for CPS skill acquisition should concentrate on collaborative games based on physical spaces in which technology based on robots is perceived by children as natural and motivating game elements.

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Chapter 11

Evaluating a Tactile and a Tangible Multi-Tablet Game for Collaborative Learning in Primary Education

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Abstract

Learning through serious games is a popular research topic nowadays, however, these games are still being developed mostly for traditional technological platforms such as video consoles and desktop computers, which complicate the design of collaborative activities since they are essentially mono-user. The recent popularization of handheld devices such as tablets and smartphones brings the potential to build affordable, scalable, and improvised collaborative games by creating a multi-tablet environment. In this paper we present Quizbot, a robot-based educational game to collaboratively solve quizzes of different nature, which can be defined by educators beforehand. Two versions of the game are implemented: a tactile one to be played with tablets on a table, in which the game elements are all digital; and a tangible one in which the tablets are scattered on the floor and the game elements are both digital and physical objects. Both versions of Quizbot are

evaluated and compared in a study with eighty primary-schooled children in terms of user experience and quality of collaboration supported. Results indicate that both versions of Quizbot are essentially equally fun and easy to use, and can effectively support collaboration, with the tangible version outperforming the other one in being able to make the children reach consensus after a discussion, split and parallelize work, and treat each other with more respect, but also presenting a poorer time management.

11.1 Introduction

Serious games have become a very popular research topic in the last decade, and have been proven to have a positive impact on behavior and learning, specifically on knowledge acquisition, content understanding, perception and cognition, affection and motivation, soft skills, and motor skills (Boyle et al., 2016; Connolly et al., 2012). Collaboration also presents a plethora of benefits for learning. Johnson and Johnson (1989) and Panitz (1999) report on more than fifty social, psychological, and academic benefits, according to the classification by Laal and Ghodsi (2012).

As previous studies reveal (Boyle et al., 2016; Connolly et al., 2012; Hainey et al., 2016), the majority of serious games are still being developed for traditional technological platforms, namely video consoles and desktop/laptop computers. These platforms, however, present several drawbacks that make them suboptimal for children. As pointed out by Nacher et al. (2015a, 2016a), they are not very intuitive; they require users to be fixed to a single location, thus preventing them from moving around and exercising; and, finally, they are essentially mono-user, which complicates the design of games to foster social abilities and collaboration.

In recent years, considerable research has highlighted the benefits of digital tabletops in education (e.g., Catala et al., 2012a,c; Dillenbourg and Evans, 2011; Reski et al., 2014; Schubert et al., 2012), including fostering creativity (Catala et al., 2012a), knowledge acquisition and transfer (Schubert et al., 2012), and, especially, collaboration (Gutwin et al., 2006; Hornecker et al., 2008; Reski et al., 2014). Their multi-touch capabilities allow more fluid (Hornecker et al., 2008) and simultaneous interactions, which lead to increased levels of parallelism and, in turn, of performance and democratized access (Rick et al., 2011). Additionally, since face-to-face settings allow users to know what the others are doing, workspace awareness is also enhanced (Gutwin and Greenberg, 2002), which facilitates the coordination of the activity (Gutwin and Greenberg, 1998). According to Hornecker et al. (2008) this awareness increases collaborative performance and leads to better results. Despite the studies that have shown these advantages, it is not common to see tabletops embedded in actual educational settings. This, as explained by Garcia-Sanjuan et al. (2015a, 2016b) might be due to a number of reasons: a) their high cost; b) their form factor that prevents their use in scenarios requiring mobility and that keeps the device fixed to a single location, forcing the users to move to a specific place if they want to engage in a collaborative activity; c) their limited workspace dimensions, which can only accommodate a certain number of participants, even though it has been observed that in some scenarios the users tend to form groups dynamically—i.e., they tend to come and go (Marshall et al., 2011); and d) the fact that the interaction surface is always a public space in which some private tasks are impossible. To cope with these disadvantages and, at the same time, to take advantage of the benefits of tabletops in terms of awareness, parallelism, and fluidity of the interaction, we propose in this paper a different approach to tabletops that is based on handheld devices. Devices such as smartphones or tablets are nowadays very affordable and nearly in common use. Since they are small and mobile, users are able to form improvised groups virtually anywhere. By following a “Bring Your Own Device” (Ballagas et al., 2004) scheme, it is possible to build Multi-Display Environments (MDE) to support co-located collaborative educational activities on a table-like setting by coordinating interaction across these devices. In addition, if the devices are scattered over a large area, physical activity can be encouraged, which is a key factor in children’s development (Tomporowski et al., 2011) and is beneficial for supporting the construction of a positive social space for collaborative learning (Malinverni and Burguès, 2015). This would avoid the problems identified by Seitinger (2006), who points out that this type of device does not encourage full-body motion. Their size and form also allow for dynamically expanding and contracting the workspace as needed, easily done by simply adding or removing devices from the environment. Finally, mobile devices enable the synergy of public and private spaces, since switching from one to the other can be easily done by covering or tilting the device.

How to interact with these multi-tablet environments is therefore a critical issue. Mobile devices are designed to be interacted mainly via touch, which is very straightforward even to the youngest of children (Nacher et al., 2014b, 2015b). According to Shneiderman et al. (2009), direct touch enables natural interactions for three reasons: a) the visibility of objects and actions of interest; b) the replacement of typed commands by pointing actions on the objects of interest; and c) the rapid, reversible, and incremental actions which help children to keep engaged and give them control over the technology avoiding complex instructions that complicate the interaction. These interactions, however, are usually limited to the small area of the displays, which can lead to the occlusion of the screen and the underuse of the peripheral space. In contrast, Tangible User Interfaces (TUI) offer interaction through the manipulation of physical objects, which present an added value in childhood education “as they resonate with traditional learning manipulatives” (Strawhacker and Bers, 2014) and enable the exploration of the physical world, which “facilitates both the acquisition of information about, and experience with, the environment, together with exploration of different combinations of information” (Price et al., 2003). Despite these advantages, there are not many works that make use of tangible interactions in tablet-based MDEs (Garcia-Sanjuan et al., 2016c).

In our opinion, future learning environments that target collaborative learning must support negotiation, planning, communication, and organization. This work is a first step towards understanding how MDEs based on tactile versus tangible interaction can effectively support the development of these skills among primary school children. In this respect, the contributions of this paper are threefold: First, a multi-display game using handheld tablets to be used for collaborative learning is presented. The game is based on solving quizzes with different types of questions, which can be defined by teachers beforehand. To enforce collaboration, the students must negotiate and plan the actions to take in order to conjointly drive a robot to the correct answers. Second, two versions of the game are compared in terms of the quality of the collaboration they support through a study conducted with eighty primary-schooled children. These versions differ on workspace size and interaction modalities—touch and tangible. Finally, the user experience of the children with both platforms is reported.

11.2 Background

Connolly et al. (2012) and Boyle et al. (2016) conducted two systematic reviews in which they identified a total of 272 studies from 2004 to 2014 that reported empirical evidence of the impact of serious games on learning and engagement. Out of these, they only found 5 (less than 2%) relying on mobile devices. Similarly, Hainey et al. (2016) identified 105 studies from 2000 to 2013 specifically concerning primary education, and found that only 4 of them (less than 4%) relied on mobile devices. These findings reveal that traditional serious games have been developed mostly for other platforms such as personal computers or video consoles. However, as handhelds are becoming more and more widespread and they are revealed as facilitators of more natural interactions (Nacher et al., 2016a), more educational solutions are being developed for them. This section reviews research trends on serious games for mobile devices, paying special attention to two types of interaction modalities: tactile and tangible.

11.2.1 Serious Games for Tactile Mobile Devices

Several studies have previously designed serious games for mobile devices. Since these platforms are often considered private, the games they support are usually individual, in which collaboration is not always sought (e.g., Amresh et al., 2015; Browne and Anand, 2013; González et al., 2014; Molnar and Kostkova, 2016; Radu et al., 2015). Although many researchers have considered collaborative serious games for these platforms, the interaction with the device has been kept mainly private.

The first mobile serious games relied on mobile phones or Personal Digital Assistants (PDA). In Mobile Stories (Fails et al., 2010), each user is given a mobile phone connected to a server from which they can download some contents (text, images, etc.), modify them, and upload them again later. Each device can either contain a whole piece of content or part of it. In the latter case, two students can join their phones to complete the piece. This way they are expected to search for other players and join contents to collaboratively create a story. Similarly, PiCoMap (Luchini et al., 2002) enables students to create a concept map, pass it to a partner for them to annotate, and then give it back to its owner.

The recent popularization of smartphones and tablets has enabled more natural interactions thanks to multi-touch technology and embedded sensors such as camera and GPS. Kiwi Mobile (Lee et al., 2016) is an outdoor mixed-reality game aimed at helping players learn how a fictional phone manufacturing company works. By using geo-localization, the physical locations the players move around are mapped to virtual learning nodes (e.g., an interview with a game character, newspaper articles, and other game artefacts) that are triggered and displayed on screen when a user arrives to a specific location. The game is played in pairs, each member having to visit different locations. After the game, they gather at the classroom to discuss and share ideas. Moving indoors, SecretSLQ (Fitz-Walter et al., 2012) aims to teach the purpose and functioning of a library. The players can team up and explore the library searching for QR codes to unlock clues and answer questions on their device.

The works described above present several similarities. First, they take advantage of the devices' size and shape and stimulate physical mobility. Second, they focus on specific learning domains, and do not provide a way for the teachers to change the educational contents. Finally, even though they aim to foster collaboration and socialization, they usually have one user interacting with their own device or, if several participants are gathered around the same display, interaction can be easily monopolized by one of them, making the others adopt a more passive role. Even if some cues are given on each device of other players' progress, the workspace awareness enabled is low, since the users cannot see all the actions the others are doing. As a counterexample, Geney (Mandryk et al., 2001) does enforce collaboration by making impossible for a user to play alone. In this game, each child is given a phone in which they have a pond of fish with certain genetic traits. The purpose is to create new breeds of fish with different genes by mating them. To do that, the children have to necessarily exchange their fish with their classmates through the device's infrared port.

Other authors opt by fostering collaboration through communication in detriment of physical mobility, by seating players together. Mitgutsch et al. (2013) designed Movers and Shakers, a collaborative game to introduce youngsters to some communication difficulties that take place in a workplace. Played in pairs, each user is seated in front of the other and given their own tablet. Each player has a personal goal that is in direct conflict with their partner's, and the game encourages them to communicate and solve their opposing ideas in order to achieve a higher, common, objective. Since the devices are considered private instruments, each user can see the results of the other's actions on their own screen and then engage in a conversation, but they are not fully aware of what the other is doing. Instead, having a multi-tablet setting in which the devices were placed on a table publicly available would enable both users to see the other's actions at all time, which would increase workspace awareness, hence increasing collaborative performance (Hornecker et al., 2008). In this respect, Proportion (Rick, 2012) is a collaborative game that gathers two children in front of a shared tablet to help them learn about proportions and ratios. They have high awareness of what the other player is doing, and they can communicate, but collaboration is not enforced since one user can monopolize all interactions. Besides, since only one tablet is used, the workspace area is very limited.

11.2.2 Serious Games for Tangible User Interfaces

As researchers like Soute et al. (2010) showcase, creating games in which interaction transcends the boundaries of a display by making the children interact with tangible objects can enable fun experiences and stimulate social interaction and physical activity. In their work, the authors present what they call "Head Up Games," which are intended to reminisce traditional games such as tag or hide-and-seek. The games they present, however, do not have an educative motivation underneath. In Marshall' words (2007), "tangible interfaces might be particularly suitable for collaborative learning. They can be designed to create a shared space for collaborative transactions and allow users to monitor each other's gaze to achieve interaction more easily than when interacting with a graphical representation on a display. They might also increase the visibility of other member's activity, better communicating the current state of their work and potentially encouraging situated learning." In this respect, Stanton et al. (2001) design a TUI for collaborative storytelling. Multiple children are gathered around a big vertical screen that displays the different drawings that compose a given story. They can then navigate through the drawings by walking on a "magic carpet" on the floor. This carpet has multiple pressure sensors underneath that trigger different operations when stepped on: pan left/right, and zoom in/out. If multiple sensors are pressed simultaneously, the operations are summed, so the children have to coordinate themselves to perform sensible actions. To move the drawing up and down, they possess two physical props that have to be shown to a camera. By placing different barcodes in front of said camera, new drawings are displayed on screen. The authors suggest that collaborative work can be encouraged by using big-sized TUIs and physical props, because the latter slow down the pace of interaction and increase the effort required to make manipulations, which entails more communication and discussion among the students. Live LEGO House (Portalés et al., 2007) is a Lego-based tangible interface aimed at teaching coexistence and multicultural factors through an Augmented Reality game. The players configure the house furniture on a board using Lego blocks and introduce to the game tangible dolls that are tracked by a webcam. A vertical computer screen augments the scene with video and sound. This digital feedback is adapted to what the dolls are doing in the board, providing the necessary restrictions in order to enable learning. For example, if a doll is "sleeping" in bed, another will not be able to listen to the radio or watch TV. AGORAS (Catala et al., 2012c) is a platform to create games through collaborative play. Although it is devised for tabletops, the players use tangible objects as containers of digital game components (e.g., entities and behaviors), which facilitates their manipulation, sharing, and reuse. This system is intended to foster creativity as well as to build games that teach concepts of geometry and physics (Catala et al., 2012a).

The previous examples, although supporting intuitive interactions and physical mobility, either rely on very basic technological devices that reduce interactivity, or make use of cumbersome hardware like big screens or external cameras that require calibration, which may prevent their implantation at some locations. Other works opt instead for bringing tangible interactions to mobile devices like smartphones and tablets. Chipman et al. (2011) present a game for young children to collaboratively learn about patterns using tablets and RFID-tagged objects. The children scan an object with the RFID reader attached to a tablet and then they paint on it with a certain color that identifies them. Later, when another child scans said object, they can draw on top of previous drawings, thereby making the painting collaborative. The game allows the players to be aware of what each child has made, and to communicate with one another to ask who is represented by a given color, however, the communication fostered here is quite naive, and even though the children collaborate to reach a common goal, they perform their tasks individually. Another example is by Georgiadi et al. (2016) with a mobile game to learn about archaeological fieldwork. The game is played in groups of four. Each group explores collaboratively a physical space looking for special objects (Bluetooth beacons) that, when approached to a tablet, trigger specific mini-games and activities on it. Even though the children can explore the environment conjointly, each group is given only one tablet, therefore restricting multi-user interactions and limiting collaboration.

As the analysis of the previous studies reveal, and in line with other analysis (e.g., Marshall, 2007), previous works on educational TUIs have usually focused on specific learning domains because the tangibles represent concepts of the domain itself. We propose instead another approach in which the educational digital contents are independent of the tangible mechanisms they are interacted with. In this line, Garcia-Sanjuan et al. (2016d) describe MarkAirs: a generic tangible interaction technique that is conducted above the tablets by manipulating fiducially-tagged cards. In their work, they describe two educational games that can rely on it: one to collaboratively solve jigsaw puzzles, and another to collaboratively learn about associations between concepts, in which the concrete educational contents can be changed to suit the children's educational curricula.

11.2.3 Comparison of Tactile and Tangible Interactions

Aside from previous comparisons between digital and physical (traditional) interfaces (e.g., Finkelstein et al., 2005; Gire et al., 2010; Zacharia and Olympiou, 2011), several previous studies have compared fully digital and tangible user interfaces in collaborative settings, however, they tend to focus on technical aspects or individual user experience rather than on how they can support collaborative learning. Xie et al. (2008) compare children's engagement and enjoyment on three interfaces for solving jigsaw puzzles in pairs: one fully physical, another fully digital (running on a laptop and controlled by mouse), and a TUI, which enhances the physical jigsaw pieces with digital video and audio feedback. Whereas traits of collaboration are observed in all three versions, the digital one suffers from having only one mouse, which forces one child to adopt a more passive role in which they can only point at the screen and/or give verbal instructions to their partner, who has the control. In the tangible and physical versions, the participants are more effective as they parallelize their actions. However, no significant differences are observed for children's self-report of enjoyment among the three conditions. Fails et al. (2005) conduct a comparative study between a TUI and a desktop-based interface for a collaborative game to teach children about environmental health hazards and how to avoid them. After gameplay, they evaluate some aspects related to learning. Their study reveals some differences between the interfaces in favor of the tangible one. Not only the students express more interest in the TUI version and interact more with it than with the desktop version, but they also need less help from adults, construct more elaborated responses, and express less times not knowing the answer.

Others have compared touch and tangible interfaces, showing that neither outperforms the other in all conditions. Schneider et al. (2011) compare multi-touch and tangible interactions on a tabletop to build a warehouse by composing blocks. Their results indicate that the tangible interface presents better performance results as well as more exploration of alternative solutions, more playfulness, and more collaboration than the tactile interface. Moreover, they show that performance is strongly correlated to collaboration and playfulness in the touch condition, whereas it is strongly correlated to more exploration in the TUI. Other studies like the ones by Catala et al. (2012b); Tuddenham et al. (2010) indicate that tangible interactions are more effective to support basic manipulations such as acquisitions, translations, and rotations. However, Catala et al. (2012b) show touch dragging as more effective for exploration of digital collections in certain widgets. As the analysis of these studies reveals, comparisons between tactile and tangible interfaces have been conducted mainly with tabletop devices, and not much work has been done in this respect with tablets. As a counterexample, Bock et al. (2015) do conduct a comparison of touch and tangible interactions on a multiplayer game played on a single tablet. The study evaluates the users' preference for one or the other interface, but no significant results are obtained. Regardless of the interactive platform, these works only consider tangible interactions on the digital screen. In this respect, Jadan-Guerrero et al. (2015) conduct a comparison between a touch and a tangible interface for tablets in which touch occurred on screen whereas tangible interactions take place around the device, thus preventing screen occlusion. The evaluation conducted focuses on the experience children with Down syndrome had with a literacy application, and results suggest tangible manipulations being easier as well as fostering more verbalizations. However, again, this study only considers collaborative teacher-student learning in the context of a single shared tablet.

In sum, comparisons between tangible and touch interactions have usually focused on technical aspects and have been conducted for tabletops, with tangible interaction being performed on the screen itself. To our knowledge, no previous

Figure 11.1: Quizbot's game board in its tactile version. Augmented view of a selected item.

works have considered comparing these interaction modalities in terms of their implications for designing an activity with an MDE in which interaction spans across multiple devices and can happen outside the display. In this paper we study these implications for collaborative learning through a serious game deployed on a multi-tablet setting in two modalities: one fully digital and tactile, and another tangible.

11.3 Quizbot: A Multi-Tablet Game for Collaborative Learning

Gamification, or gameful design, is defined by Deterding et al. (2011) as "the use of design elements characteristic for games in non-game contexts." Therefore, for the design of the collaborative learning game, the five game dynamics identified by Bartel et al. (2015), in accordance with the definition by Deterding et al., were taken into consideration. These dynamics are: *constraints*, *relationships*, *narrative*, *progression*, and *emotion*.

Quizbot (see Figure 11.1) was designed as a tablet-based MDE to foster collaboration by means of several general *constraints* that were considered during the game design. First, the game dynamics would need the joint intervention of several players simultaneously so that no single child could make progress in the game playing alone. Second, the game would require the exploration and discussion of different choices of action and the definition by the players of a goal to achieve as a team by means of communication, planning, and negotiation. Finally, the game would require the continuous coordination of actions during game play in real time to achieve the predefined goal. These constraints were also designed to promote a collaborative *relationship* between the players.

Taking into consideration the *narrative* and *progression* dynamics of Bartel et al., a simple design was adopted that would force players to concentrate on the collaboration dimension rather than on understanding complex game rules or procedures. Quizbot is, in essence, a board-based quiz game. The board itself has an undetermined number of cells with "items" placed on top, and the main actor is a robot that the players can move by using a set of movement commands (i.e., go forward, stop, turn left, or turn right). The items on the cells are keys, walls, and bombs. The keys are the main items on the game. When one is reached by the robot, it will display a question, and the rest will populate with possible answers. The goal is then to lead the robot to the correct answer cells in order to complete the quiz. The players have, however, to avoid the obstacles represented by the other two types of items. Walls impede the robot from passing through, whereas bombs explode on contact, making the players to lose their current progress. The reason of having these obstacles and make the players lose their progress is twofold. First, to support challenges and replays, two design elements for gamification that have been shown to foster engagement, enjoyment, and productive learning experiences (Nah et al., 2014). Second, to include *emotions* and individual versus team responsibility of failing actions as factors that may hinder or empower the collaboration depending on how they are handled by the team.

Quizbot is designed in a way that teachers can previously define the questions and answers the children will have to solve through a web app (see Figure 11.2), providing the game with enough flexibility and re-playability. Three different types of question styles are supported:

- Single/multiple Choice: The players are presented with several answers and must choose the correct one(s), visiting the cells in any order (e.g., "Which of the following energy sources are renewable?").
- Ordering: In this case, all the answers are correct but the players must visit them in a specific order (e.g., "Sort the following planets in the Solar System from smallest to biggest").
- Accumulation: These questions provide the players with a greater freedom of choice since they can choose whichever answers they want as long as their total sum equals a certain value (e.g., "Choose from several water recipients of different sizes the ones that will fill a swimming pool having a volume of $X\text{m}^3$ without exceeding its capacity").

In order to foster collaboration, Quizbot's main goal, the four movement commands to control the robot are split among the players so that they are driven to cooperate and coordinate their efforts in order to plan and execute the robot's track on the board. The design rationale behind needing four players to control the robot is because working in small groups has been found very effective in collaborative learning, since it "increases each student's opportunity to interact with materials and with other students while learning. Students have more chances to speak in a small group than in a class discussion; and in that setting some students are more comfortable speculating, questioning, and explaining concepts in order to clarify their thinking" (California State Department of Education, 1985). Specifically, Quizbot is designed to meet the six conditions for successful collaborative learning identified by Szewkis et al. (2011):

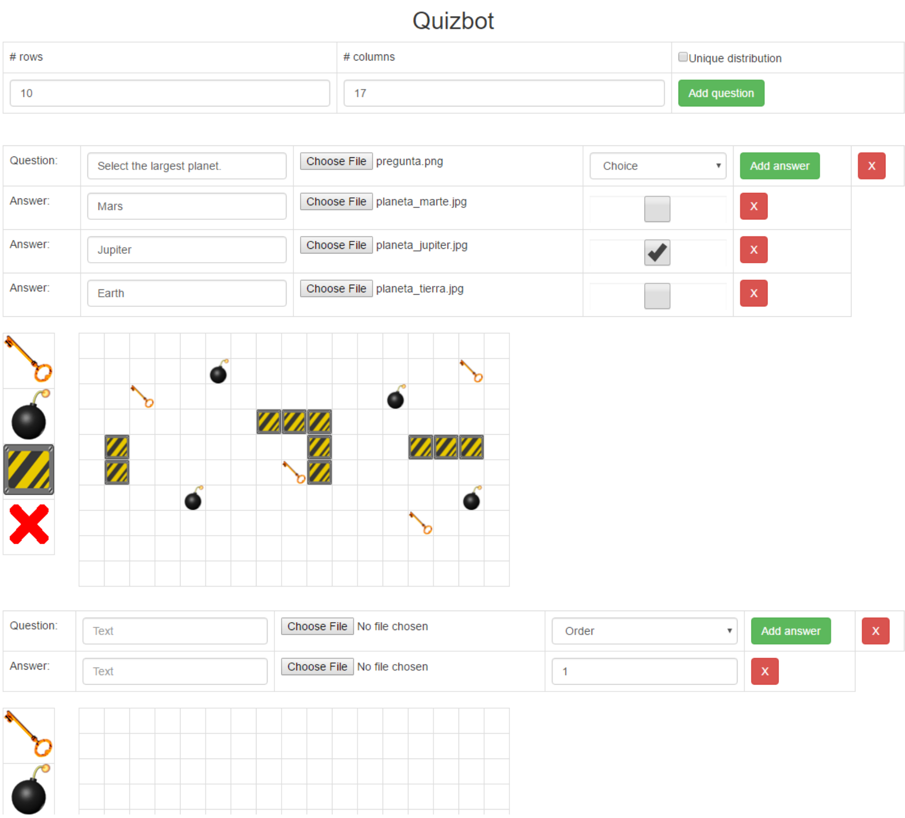

Figure 11.2: Quizbot contents' web editor.

- The existence of a common goal. By providing a common goal to all participants, i.e., making them solve the same quiz, the game enables the social interactions necessary to make the students learn through collaboration (Dillenbourg, 1999).
- Coordination and communication between peers. The students need to communicate between one another and interact in the right order and at the right time in order to solve the common goal (Gutwin and Greenberg, 2004). Since each player is in charge of giving only one movement command to the robot, they must necessarily coordinate their actions to drive the artifact to the correct answers.
- Positive interdependence between peers. The students feel connected to one another so that they feel they can only succeed as long as the rest do (Brush, 1998; Johnson and Johnson, 1999). According to Nam and Zellner (2011), whereas games that are only competitive promote negative interdependence, those that include cooperation foster positive interdependence.
- Awareness of peers' work. For collaboration to work, all participants need to be able to see what the others are doing at any time, so they can receive common feedback that will support their decision making process (Gutwin and Greenberg, 2004; Janssen et al., 2007). To support this, the tablets in the game are placed on a flat surface, publicly displayed to all users at all times.
- Individual accountability. In order to ensure their contribution, each student needs to be accountable for their actions before the others. For this, every participant must be able to see the consequences of any of their peers' actions (Janssen et al., 2007; Johnson and Johnson, 1999; Slavin, 1996). Therefore, the distribution of the robot's movement commands is conducted publicly beforehand, and that distribution is kept visible throughout the game.
- Joint rewards. As all members of the team are solving the same quiz together, they get rewarded or punished alike, which makes them constantly try to improve their collaboration (Axelrod and Hamilton, 1981; Zagal et al., 2006).

The game is implemented in two versions: tactile and tangible. Whereas the former makes only use of mobile tablets and is played on a table, the latter adds physical objects to the game and extends the size of the playground to play on the floor.

11.3.1 Tactile Version

As Figure 11.3 depicts, the tactile version of Quizbot is played on a table with only four tablets (one per player). Four participants are gathered around a physical table with four tablets laid on top. The interface is replicated among the devices so each player can have their personal view of the board, but a different button is

Figure 11.3: Instance of the game in its tactile version running on four tablets.

placed in each display representing a different movement command for the robot: turn left (Figure 11.3-top-left), turn right (Figure 11.3-bottom-right), go forward (Figure 11.3-bottom-left), and stop (Figure 11.3-top-right). Once the robot has reached a key, that cell is populated with the question of the quiz and the other keys are replaced by icons representing minimized versions of the possible answers. Due to the reduced screen space, these items are not always displayed in maximized form, but each player can explore them individually on his/her tablet by touching the corresponding cell, which will show an augmented view of the item (see Figure 11.1). The rationale behind this configuration is to enable collocated collaborative scenarios similar to the ones that take place around tabletops, with high awareness, parallelism of actions, and fluid touch interactions on the digital displays.

11.3.2 Tangible Version

With the aim of enabling a more dynamic game in which physical mobility is encouraged and still provide high levels of workspace awareness, a tangible version of Quizbot was designed to be played on the floor (see Figure 11.4). Each question/answer key cell is displayed on a different tablet to facilitate the dynamic reconfiguration of digital contents as the game progresses. They are intended to remain fixed to their location during the course of the game, so the players can view their contents at a glance even from a distance. The board, bombs, walls, and robot are physical artefacts the players can physically interact with. This version of Quizbot makes use of the Tangibot platform (Garcia-Sanjuan et al., 2017) as the physical mobile robot and its paddle-based tangible interface for its control, as it has already been proven usable for children older than 3 years old in tasks that involve following paths (Nacher et al., 2016b). However, Tangibot's design has been slightly modified by bringing its smartphone on top (see Figure 11.5-left), so that it can be used to deliver video and audio feedback to the players as different game events take place (e.g., a bomb explosion, a correct or incorrect

Figure 11.4: Instance of the game in its tangible version.

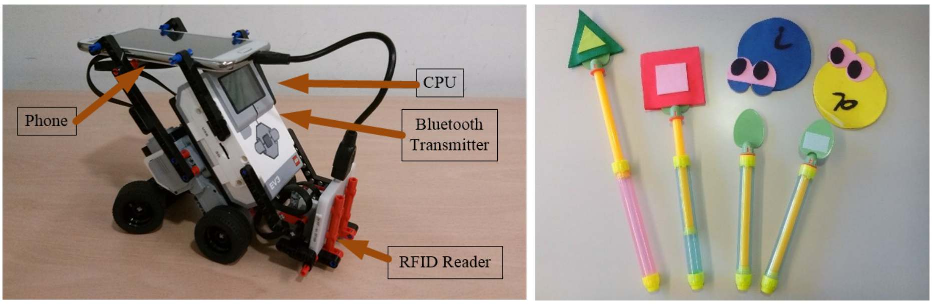

Figure 11.5: Tangibot's design for the Quizbot game (left) and paddles for its control (right).

cell has been reached, etc.). Each movement command is encoded in an RFID tag enclosed in an extensible paddle as shown in Figure 11.5-right, which triggers the corresponding movement in the robot when the players bring the paddle close to its RFID reader. Since the manipulation of the robot takes place in the real world, the game elements susceptible of triggering digital events (i.e., bombs and tablets) also have RFID tags attached underneath that are read by Tangibot's RFID reader when it approaches (see Figure 11.6).

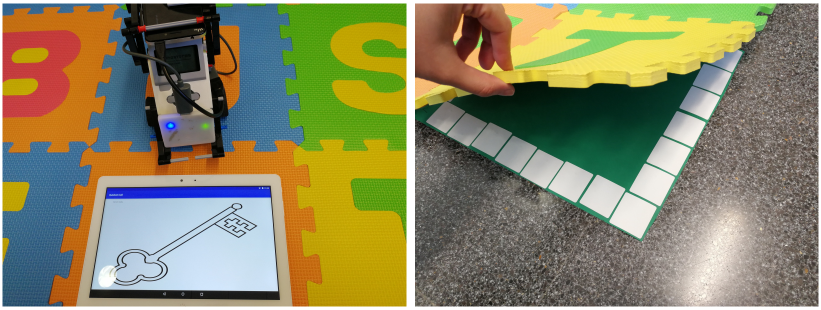

Figure 11.6: Tangibot approaching a tablet (left) and matrix of RFID tags placed below the tablet for Tangibot to recognize (right).

11.4 Evaluation

This section reports on a study to evaluate the capabilities of both tactile and tangible versions of Quizbot in terms of user experience and collaboration. Regarding the former, the research questions addressed are the following:

RQ-UX1 Do the participants find Quizbot more fun than they expected? Are there any differences between both versions of the game?

RQ-UX2 Do the participants find Quizbot easy to use? Are there any differences between both versions?

RQ-UX3 What are the general impressions of the participants towards the game in both platforms?

RQ-UX4 What changes do the participants suggest to both versions of Quizbot?

With respect to collaboration, the research question addressed was the following:

RQ-C1 How is the quality of the collaboration achieved by using Quizbot? Does it differ between the tactile and tangible platforms?

Additionally, the following research question with respect to the performance achieved was contemplated:

RQ-P1 Does the time spent in solving a quiz vary between both versions of the game?

11.4.1 Participants

Eighty children (forty-three males and thirty-seven females) of 9-10 years of age participated in this study in the context of a summer school's activity. They were not classmates since they originated from different primary schools in Valencia (Spain).

11.4.2 Apparatus

This study took place in a classroom. Both tactile and tangible versions of Quizbot were considered. With respect to the former, four tablets were arranged on a table the students had to sit (or stand, whichever they preferred) around. Each tablet running Quizbot had a different button to control a movement of the robot. As for the tangible version, the participants played on a $7 \times 4m^2$ board on the floor. The game components in both versions of the game (i.e., bombs, walls, and keys) were placed in the same relative location. There were a total of six key cells (one question plus five possible answers), seven bombs, and twelve cells were filled with walls (see Figure 11.3 and Figure 11.4). The tablets used were all 10.1" Android capacitive tablets of different brands and models. The educational contents used for both platforms were designed conjointly with primary school teachers who knew the children's educational curricula with the aim of making the questions affordable but still challenging enough to promote collaboration and fun. A total of thirty-six different questions were designed with contents about language, natural science, history, and geography.

11.4.3 Evaluation Instruments

The user experience of the participants was measured via pre- and post-activity questionnaires. Concretely, the fun expectancy and perception as well as the perceived ease of use of the platform (RQ-UX1 and RQ-UX2, respectively) was evaluated using the Smileyometer (Read, 2008; Read and MacFarlane, 2006), a 5-point Likert Scale in the form of a Visual Analogue Scale (VAS), in which the different valuations (i.e., "awful," "not very good," "good," "really good," and "brilliant") are represented by smiling faces. To answer RQ-UX3 and RQ-UX4, after playing with a platform the participants were asked to write down in a blank sheet of paper their impressions and the changes they would make (if any) to the game or to the platform they just played with.

The rest of research questions were answered by qualitative infield observation. The time spent in solving a question (RQ-P1) was calculated as the ratio between the total gameplay time over the number of questions solved, whereas the quality of the collaboration (RQ-C1) was assessed with the questionnaire designed by Meier et al. (2007). This questionnaire consists of nine dimensions associated with five different aspects of collaboration, which were filled by two independent observers after the activity in a 4-point Likert Scale ranging from -2 (very bad) to +2 (very good), with only the endpoints of the scale being named. Before the evaluation, both observers established common observation criteria based on the description from Meier et al. and adapting some dimensions to fit their actual observations, because the original descriptions were neither designed for children nor for groups of four. The different dimensions classified by the collaboration aspect they measure are described below:

- Communication

1) Sustaining mutual understanding: The students make themselves understandable to their peers by using a common language and ensure they have been understood by requesting feedback from their partners. The listeners give verbal confirmation of their understanding and ask for clarification if necessary.

2) Dialogue management: The participants let speak and listen to one another, with little time being lost due to overlaps in speech. The speakers ensure they have their partners' attention by explicitly addressing them.

- Joint information processing

3) Information pooling: The children try to gather as many pieces of information as possible. They often contribute with their own and ask the others if they do not know something.

4) Reaching consensus: The students negotiate which way to take the robot and which cells to visit and in which order, and after the discussion they come to an agreement.

- Coordination

5) Task division: The players divide their work equally among them and parallelize their actions to solve the questions.

6) Time management: The participants manage their time correctly to solve the maximum number of questions, avoiding wasting time.

7) Technical coordination: The players master the interactions necessary to successfully complete the game, achieving a fluent movement of the robot without bumping into obstacles. They also find strategies to guide the robot more efficiently.

- Interpersonal relationship

8) Reciprocal interaction: Partners treat one another with respect and encourage the others to contribute. While criticism is welcome, it is always related to the activity and never personal.

- Motivation

9) Conjoint task orientation: Every member of the team participates actively in the game. They remain focused and avoid distractions, and cheer when they answer correctly. To simplify the work to the observers, this dimension has been adapted to evaluate all members of the group conjointly instead of each participant individually.

11.4.4 Procedure

The study was conducted in two sessions two separate days of the week. Before the first session began, the children were randomly arranged in groups of four, and groups were kept unaltered during the entire study. On each day, while half the groups played with one version, the rest played with the other, and switched platforms on the second session in order to avoid carryover and learning effects. The educational contents generated were randomly split in two sets to avoid repeating questions. For each session, all groups were presented with the same series of questions and answers, and in the same order.

Before starting the activity, they were given proper instructions of the different components of the game, the main objective, and how to control the robot. Then, each member of the group filled a Smileyometer with their expectations and proceeded to play for 30 minutes while the two observers took notes. The first quiz was a training question to help the participants familiarize with the interface and the game's rules and components. After the game, the children filled the remaining questionnaires and the observers rated the quality of the collaboration they had observed.

11.4.5 Results

Performance

The time spent by each group in solving a question was, on average, 5.48 minutes ($SD = 1.45$) with the tactile version, and 4.78 minutes ($SD = 1.00$) with the tangible one. In order to answer the research question RQ-P1, a dependent t-test ($\alpha = 0.05$) was conducted, which revealed no significant differences between platforms for the dependent variable considered ($t(19) = 1.612$, $p = 0.123$).

User Experience

As Table 11.1 shows, the participants reported having high expectancies as well as high levels of perceived fun towards the game regardless the platform used, with scores between 4 and 5 in all cases (i.e., between "really good" and "brilliant"). To answer RQ-UX1 about the fun perceived by the children using Quizbot, an exact sign test ($\alpha = 0.05$) was used to compare the differences between the expectancies they had before playing and the actual fun they reported after the game. In this respect, both interfaces elicited a statistically significant ($p < 0.05$) decrease in the actual perception of fun from their prior expectancies (see Table 11.1).

Another exact sign test ($\alpha = 0.05$) was applied to check for differences between the tactile and tangible versions, however, no significant differences were found between platforms neither on the participants' expectancies ($p = 0.359$) nor on their perceived fun ($p = 0.324$).

The children's perceived ease of use towards both tactile and tangible interfaces (RQ-UX2) was also analyzed, this being in both cases close to "really good." For the tactile version, the perceived average ease of use was 3.94 ($SD = 1.19$), whereas

Table 11.1: Results of the exact sign test to compare the differences between fun perceived with respect to the participants' expectancies for both platforms of Quizbot.

Measure	**Tactile version**	**Tangible version**
Avg. fun expectancy (and SD)	4.75 (0.65)	4.86 (0.39)
Avg. fun perception (and SD)	4.38 (0.98)	4.62 (0.76)
Number of negative differences (perception < expectancy)	24	17
Number of positive differences (perception > expectancy)	6	5
Number of ties (perception = expectancy)	48	49
p-value	0.002	0.017

for the tangible version it was 4.09 ($SD = 1.14$). An exact sign test ($\alpha = 0.05$) reported no significant differences between the two ($p = 0.178$).

With respect to RQ-UX3, only 32.5% of the participants wrote down their impressions towards the game in its tactile version, and only 25% of them towards the tangible platform. Figure 11.7 shows a classification of such impressions and displays the frequency of occurrence of each impression in the questionnaires. The comments made by the children were arranged in groups according to the target of their impressions, namely the game itself (quiz game), the devices used (hardware), the board the robot moved across (board), either the buttons or the paddles to control the robot's movements (control mechanism), and the other members of the group playing conjointly (partners). As it can be seen in the figure, the more frequent comments were about the ease of use of the tangible user interface and the nice-looking graphical user interface (around 30% of the comments made for each platform). With respect to the tactile version, around 20% of the comments expressed the desire of the children of taking the tablets home. Even though 18.2% of the impressions explicitly stated the tactile version was easy to control, 9.1% reported the opposite. As for playing with others, 9.1% of the impressions given reported the children having liked playing in teams, whereas 18.2% were about complaints of children being yelled at by their teammates upon failing a question. The tangible platform did not receive as many impressions: there were a total of 27.8% positive comments about the game being fun, about the children liking the questions, and about being excited to win. No comments to this respect were made for the tactile platform. Additionally, 16.7% of the impressions praised the fact of having actual objects to represent the bombs.

The children were also asked to write down any changes they would make to any version of Quizbot (RQ-UX4), but only 15% and 22.5% of them suggested changes to the tactile and tangible platforms, respectively. The proposals they made are shown in Figure 11.8 with the frequency of their occurrence in the questionnaires. As can be seen in the chart, the more frequent proposal for each

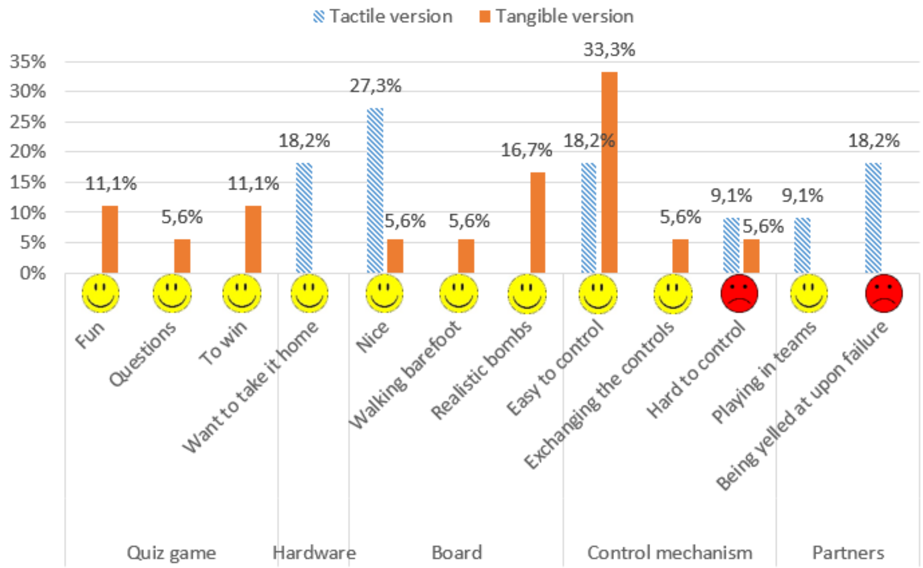

Figure 11.7: Frequency of participants' impressions towards both versions of Quizbot, classified by the target of the comment. The smileys indicate whether the comment was positive or negative.

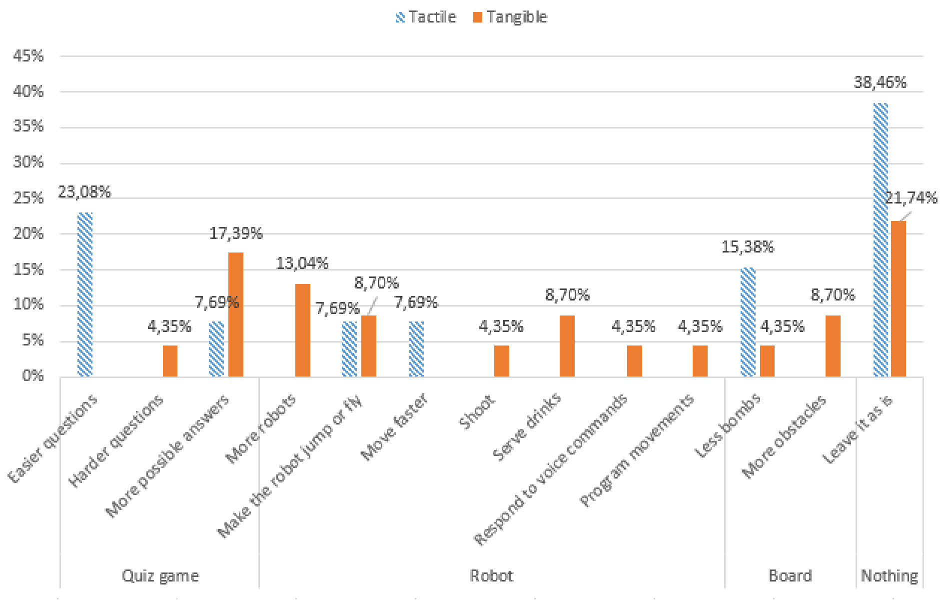

Figure 11.8: Frequency of participants' change proposals to both versions of Quizbot, classified by the target of the comment.

platform was explicitly to make no changes and leave the game and platform unaltered, however, the students suggested other improvements, such as changes to the game itself (quiz game), to the robot's capabilities (robot), and to add or remove elements from the board (board).

Collaboration

Figure 11.9 depicts the scores for each collaboration dimension and for each Quizbot version as the mean values calculated by two observers for all twenty groups of four participants. Krippendorff's α was used to calculate inter-rater reliability for each dimension. The results reveal good reliabilities in most of the dimensions under analysis ($\alpha > 0.8$, according to Krippendorff, 2004), as can be seen in Table 11.2. However, the "sustaining mutual understanding" and "dialogue management" dimensions present an absence of reliability ($\alpha = 0$) due to reduced intra-coder variability (i.e., each observer rated almost all teams equally), however, a deeper look into the ratings revealed that the observers agreed on more than 90.00% of the cases for both dimensions and both platforms.

A Wilcoxon signed-rank test ($\alpha = 0.05$) applied to each dimension showed that the students behave significantly different ($p < 0.05$) with the two platforms evaluated in reaching consensus, task division, reciprocal interaction, and time

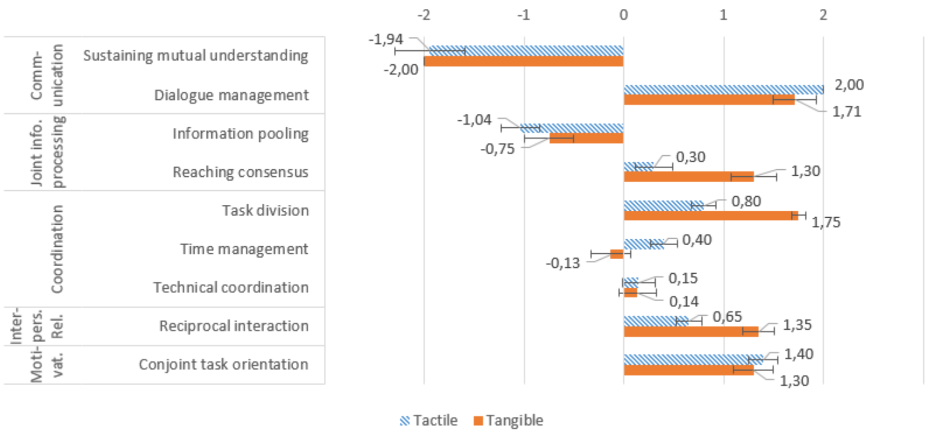

Figure 11.9: Scores for each communication dimension (calculated as the mean score from the two observers).

Table 11.2: Krippendorff's α values for each communication evaluated by the two observers in each platform, and Z and p-values from the Wilcoxon test to check for differences among platforms for each dimension.

Dimension	α **(tactile)**	α **(tangible)**	Z	p**-value**
Sustaining mutual understanding	0.0000	0.0000	0.000	1.000
Dialogue management	0.0000	0.0000	-1.414	0.157
Information pooling	0.8773	0.8120	-0.834	0.404
Reaching consensus	0.8276	0.8158	-2.709	0.007
Task division	1.0000	0.8560	-4.363	0.000
Time management	0.8811	0.9213	-2.417	0.016
Technical coordination	0.8495	0.9106	-0.535	0.593
Reciprocal interaction	0.8874	0.9824	-3.540	0.000
Conjoint task orientation	1.0000	0.9222	-0.744	0.457

management, with the tangible version outperforming the tactile one in all of these dimensions except the latter.

11.4.6 Discussion

The results obtained reveal Quizbot to be perceived by children as an engaging game in general, with fun being rated between "really good" and "brilliant" on average. As reported by the observers, the players were in a constant state of flow, i.e., fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity (Nakamura and Csikszentmihalyi, 2008), which has often been considered a key factor to promote learning (Rathunde, 2003; Shernoff et al., 2003). Quantitatively, however, the fun perceived by the children was slightly but significantly lower than what they expected when first introduced to the game. This might be related to the fact that some participants expressed their desire to make some changes to the game, even though most of them explicitly reported not wanting to change anything. Although there were some overlaps, these changes were generally different for the two versions. For the tactile one, the students mostly expressed their desire of making it simpler, with 34.46% of the comments asking for easier questions or less bombs. Surprisingly, the tangible version, which had the same number of obstacles and in the same location, and had questions of similar difficulty, arouse opposite change wishes, since 39.13% of the changes were about adding more possible answers, more robots, or more obstacles. This, conjointly with the fact that some children expressed wanting the robot to move faster in the tactile version (whereas none of them did for the tangible one) might indicate that the participants enjoyed more interacting with the tangible interface.

The platforms considered were not found significantly different on the time the children spent solving a question nor on their ease of use, this being evaluated by children close to "really good" in terms of Read's Smileyometer. This was somewhat expected for the tactile version since children nowadays are quite accustomed to playing with mobile tablets, yet it reinforces previous findings in the literature about tangible user interfaces being very intuitive and easy to use. The ease of use of the paddle-based control mechanism might have surprised the children as well, seeing that it was the most frequent positive impression remarked towards the tangible platform with a 33.3% of occurrence.

Results also indicate that both versions of Quizbot support overall good collaboration quality, with all dimensions but "sustaining mutual understanding," "information pooling," and "time management" in the tangible version being rated positively. A discussion with the observers revealed some insights about why the students performed worse in these dimensions. "Information pooling" was rated close to "bad." Even though children sometimes asked their teammates for help, their explanations were not very elaborate, and mostly consisted of giving orders to one another. "Sustaining mutual understanding" received the lowest scores, being rated close to "very bad." This was due to the children not being concerned about whether their peers understood or not their explanations. When children expressed their opinion, they moved on with the game, and if they later found out that their peers had not understood them, they repeated their explanation again. These results could suggest either a game deficiency in supporting collaboration, or a limitation of the questionnaire defined by Meier et al. (2007) when used with children, since some dimensions were initially devised to be applied to adults, who have higher communication skills. "Time management" in the tangible version, although close to 0 (neutral), was also rated negatively. This was probably due to the novelty effect the platform had on the children, which made them spend much time playing with the physical props on the board and running around. Surprisingly, the time to solve the questions does not significantly differ between platforms, which can be explained by the children being more precise in controlling the robot and not colliding as much with the walls and bombs when using the tangible version, which, as reported by the observers, was more frequent in the tactile version. Besides "time management," both versions of Quizbot did show significant differences on several collaboration dimensions, namely "reaching consensus," "task division," and "reciprocal interaction," in which the tangible platform outperformed the tactile one. The reason why reciprocal interaction was significantly perceived lower in the tactile version could also be explained by the fact that the players seemed to collide more with bombs, hence losing their progress, which caused the children to blame one another. These reprimands and critics were not always constructive, and would had probably irritated the participants. This would also explain why 18.2% of the impressions regarding the tactile interface were about children disliking being yelled at when making a mistake. Task division being significantly better in the tangible interface is probably associated with the fact that each tablet represented a key (question/answer) cell in the game and they were scattered on a big board the children could move around. A frequent pattern emerged in this platform: when a question appeared, the children would disperse on the board to explore the answers, and would inform the others about the ones they had seen, thereby parallelizing more their work. In the tactile platform, however, they tended to explore all the cells individually, and then negotiate which ones to visit. This is probably due to them being accustomed to use mobile devices individually. Finally, reaching consensus was also perceived significantly higher in the tangible version than in the tactile one. This was so because in the tactile version the students tended to negotiate only which cells to visit but in the tangible version they also negotiated which path to take the robot on in order to drive it through the shortest or safest (bomb-free) way, and helped their arguments by moving themselves on the board. This was harder to achieve in the tactile version because the game world was embedded in a small screen, even though it was sometimes observed that some children stood up and pointed the way on each partner's tablet.

It was also observed during the game that Quizbot's design enabled meeting all six conditions for successful collaborative learning identified by Szewkis et al. (2011), namely having a common goal, joint rewards, awareness of the others' work, individual accountability, coordination and communication between peers, and positive interdependence. Three components of its design were responsible for this: the rules of the game itself, the layout and interaction of/with the different props and devices, and the collaborative relationships supported. The different game constraints and rules, including having a common goal and joint rewards for all participants, made collaboration fun. As reported above, the children were in constant state of flow and enjoyed playing with others. Having a flat layout in which all game elements were distributed on a public surface for all users to see and access enhanced workspace awareness, as expected. It was observed that children frequently referred to certain parts of the board by pointing at them with their finger or by referring to them using demonstratives (e.g., "let's go *there*"), which simplified communication and helped them maintain their focus. The interaction with the platform via distributed controls among the participants facilitated the users being accountable for their actions before the rest. Indeed, they were constantly aware of which partner was in charge of which movement command, which they often used to address one another (e.g., "now you turn right!," "where is the one who stops it?"). This design to promote awareness and individual accountability sometimes led to the situation described above of having a child being recriminated a failure, but it also enabled congratulations upon success and situations in which the children identified a potential "expert" in a given topic because they had previously answered correctly a similar quiz, which increased the group's performance. Finally, Quizbot fostered collaborative relationships which supported coordination and communication (discussed above) as well as positive interdependence, which emerged not only because the game constraints prevented them from completing a quiz individually, but as a result of the players feeling as part of a team, as suggested by multiple uses of first person plural forms such as "we won!," "we need to go there," or "we should first think about which ones are correct."

In general, it can be inferred from the study conducted that Quizbot is a fun and engaging game that effectively supports collaboration, exploration, and reflection, which, according to Price et al. (2003) are key to successfully develop playful learning activities. However, the results also suggest that some changes could be made to Quizbot's design in both platforms in order to make it more appealing and to better support collaborative learning. First, the teacher should design both the questions and the board layout (i.e., obstacles) according to different difficulty levels, so that the players could move on to harder levels progressively. Second, additional capabilities to the robot (e.g., jumping, moving at different speeds, etc.) should be considered and studied, for it might increase fun in detriment of content comprehension (Achtman et al., 2008; Aleven et al., 2010). Similarly, having a robot per user acting as an avatar might increase children's motivation, but the game dynamics should be revisited to still support Szewkis et al.'s requirements for collaborative learning (2011), such as having a common goal. In order to improve the quality of the communication in terms of sustaining mutual understanding and information pooling, the quizzes defined could be more open ended or require a more elaborate resolution procedure for the children to have more time to expose and discuss their opinions. With respect to the digital version of the game, task division and reaching consensus might be improved by having an extended-continuous logical view of the multi-tablet environment (Garcia-Sanjuan et al., 2016c), i.e., having each display to show a partial view of the board. This way the game elements could be bigger and the players might parallelize their explorations and discuss alternative paths for the robot as it happened with the tangible version. Additionally, a combination of both platforms presented in this study could be developed in order to create a hybrid tactile/tangible version of Quizbot to be played on a table. A smaller physical robot would be moved among the tablets, and, by using technology to track the tablets on the table (e.g., Garcia-Sanjuan et al., 2016b; Rädle et al., 2014), the whole table would serve as the board whereas the tablets act as "peepholes" that show the digital world as they are moved, thereby having an extended-discontinuous logical view of the MDE (Garcia-Sanjuan et al., 2016c).

11.5 Conclusions

This work has presented Quizbot, a collaborative serious game in the form of a tablet-based MDE that consists of solving quizzes by conjointly driving a robot. It comes in two interaction modalities: tactile and tangible. Whereas the tactile version is played with different tablets arranged on a table the players gather around, the tangible version combines the screens with physical props scattered on the floor. Both versions seek to take advantage of handheld devices to build affordable, improvised, scalable settings that provide intuitive, fluid, and simultaneous interactions; high workspace awareness; and, in the case of the tangible platform, physical mobility; all to enable collaborative learning.

A study conducted with eighty primary-schooled children has revealed that both platforms are equally valid to provide a fun experience through a serious game, and no interaction mechanism has emerged as significantly better than the other in terms of performance or ease of use. An analysis of the quality of the collaboration around nine dimensions has revealed both versions enabling good collaboration overall, with the tangible platform outperforming the tactile one in being able to make the children reach consensus after a discussion, split and parallelize work, and treat each other with more respect. Nevertheless, it has also been observed that the participants managed their time more poorly with the tangible platform, probably due to being overwhelmed by having so many physical props to interact with.

From the results obtained, several design changes to the educational contents and the interactive elements have been proposed. These consist of presenting the quizzes to the children in increasing level of difficulty, and making the questions either open ended or that require an elaborate resolution procedure to trigger more conversations. Additionally, other major changes have been proposed that should be properly studied in terms of their suitability to promote collaborative learning. These include extending the robot's functionality with the ability to jump or to move at different speeds, adding more robots to the game, and also to combine both interaction modalities into a hybrid tactile-tangible platform to be played on a table with location-aware tablets.

Acknowledgments

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Part IV

Related Exploratory Work

Chapter 12

From Tabletops to Multi-Tablet Environments in Educational Scenarios: A Lightweight and Inexpensive Alternative

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Abstract

This work introduces a Multi-Display Environment (MDE) based on handheld devices to build tabletop-like experiences in an affordable, scalable, and simple way to foster collaboration in educational settings.

12.1 Introduction

A myriad of studies in the literature (e.g., Catala et al., 2012a,c; Reski et al., 2014; Schubert et al., 2012) highlight the multiple benefits of using digital tabletops in education, including fostering creativity (Catala et al., 2012a), learning, knowledge transfer (Schubert et al., 2012), and, especially, collaboration (Hornecker et al., 2008; Reski et al., 2014). However, it is not common to see tabletops embedded in actual educational settings because of several reasons: their high cost; their form factor that prevents their use in scenarios requiring mobility and, consequently, preventing the users to form improvised groups virtually anywhere; the fact that the interaction surface is always a public space in which some private tasks are impossible; and their limited workspace dimensions, which can only accommodate a certain number of participants. To cope with these disadvantages and, at the same time, to take advantage of the benefits of tabletops in terms of awareness (Gutwin and Greenberg, 2002; Hornecker et al., 2008), parallelism (Rick et al., 2011), and fluidity of the interaction (Hornecker et al., 2008) we propose a different approach to tabletops that is based on common-use handheld devices such as tablets. Following a "Bring Your Own Device" (Ballagas et al., 2004) scheme, it would make it possible to build Multi-Display Environments (MDE) to support co-located collaborative educational activities on a table-like setting by coordinating interaction across these devices. This paper describes a low-cost scalable table-like MDE to be used in educational settings, which do not require any complex or expensive hardware setup. It consists of two main components: WeTab, a tracking mechanism to maintain all tablets in the same logical workspace and enable real-time reconfigurations; and MarkAirs (Garcia-Sanjuan et al., 2015c, 2016a), a cross-device interaction technique that takes place above the displays and enables the exploit of the physical space surrounding the tablets. As an Around-Device Interaction (ADI), MarkAirs complements touch to take advantage of the surroundings of the device in order to, for example, extend their interaction area, or to acquire elements out of reach.

12.2 Technological Infrastructure

12.2.1 WeTab: Tracking the Devices

In line with the approach by Maciel et al. (2010), the proposed environment is comprised of a regular table on which the activity takes place, with several tablets arranged on it to provide digital contents, and a wallpaper on the ceiling that serves as a common reference for all the tablets (see Figure 12.1 and Figure 12.2), but unlike the others, our markers can be images like photos or wallpapers. This makes the creation of new markers easier (and even fun), and enables easy extending of the working area by juxtaposing several images on the ceiling. Each tablet runs Vuforia™ computer vision algorithms based on natural feature tracking, which allows extracting the wallpaper's current pose matrix $P_r = [R_r|t_r]$, where R_r is the rotation matrix and t_r the translation vector of the reference image. Since R_r is orthonormal, the device's virtual camera model $P_c = [r_c|u_c|d_c|t_c]$ (where t_c is the translation vector and r_c, u_c, and d_c are the vectors which define the device's

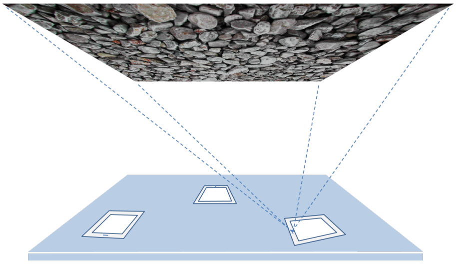

Figure 12.1: Schema of the proposed MDE using WeTab, in which each tablet can track its relative pose with respect to the marker on the ceiling.

Figure 12.2: MDE using WeTab with several tablets on a table (left) and the reference image/marker on the ceiling (right).

orientation, as can be seen in Figure 12.3) can be obtained by performing a simple mathematical transformation (see eq. 12.1).

$$P' = \left(P^{-1}\right)^T = \left[R^T|{-R^T t}\right]^T \tag{12.1}$$

12.2.2 MarkAirs: Interacting Above the Surface

MarkAirs is an interaction technique performed above a tablet and is conducted by handling a fiducial marker which, when in the field of view of the device's built-in front camera, allows a computer vision software to detect the marker and track its 6-DOF pose (position and orientation) in real-time (see Figure 12.4). Markers may be attached to physical cards or displayed on other digital devices (see Garcia-Sanjuan et al., 2015c). In this approach, the markers consist of arbitrary drawings which are tracked by the natural feature tracking algorithms of Vuforia™. We adopted these particular markers for several reasons: First, because they can be tracked even if they are partially occluded (see the bottom-left corner of the tablet in Figure 12.4, which shows the image captured by the device's camera).

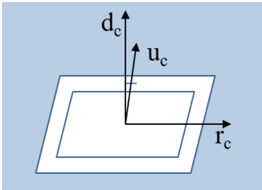

Figure 12.3: Device's virtual camera model.

Figure 12.4: Interaction with MarkAirs.

Second, because they enable precise fine-grained manipulations (Garcia-Sanjuan et al., 2016a). Third, because this system allows for a virtually infinite number of markers. And, finally, because a marker can also be a meaningful photograph, which can be related to the digital information content that is associated with the card (e.g., if we want a card to contain a game character, the marker can be a picture of the character itself). With MarkAirs, users can perform several manipulations that can be used to complement simple touch. For instance, they can control virtual elements with precision by mapping the translation vector and/or the 3-DOF rotation information of the marker to a digital element on the screen. Also, gestures can be made in the air to trigger specific actions in the tablet. Markers can behave as containers of digital elements, which can help to avoid cluttering on the screens and be seamlessly transferred across devices. Additionally, since each marker has an ID encoded, users performing certain manipulations can be identified and their performance tracked. These manipulations involve a single marker and a single device at a time, however, if used in conjunction with WeTab, in which all the tablets are aware of each other's position and orientation, more elaborate cross-device interactions can be achieved, such as pointing to remote tablets from the one that is currently tracking the marker.

12.3 Potential Educational Activities

The MDE proposed in this paper represents an affordable and scalable way of building tabletop-like experiences virtually anywhere, and also considers the physical space above and around the surfaces. We thus believe the benefits of tabletops in terms of awareness and collaboration are applicable to this environment, making it suitable to host educational activities. On the one hand, WeTab would allow building educational games based on peephole navigation, where the students have to collaboratively discover parts of a "hidden" virtual world by moving the tablets on the table. They could for example discover maps (see Figure 12.2-left) or hidden pieces to solve a puzzle. On the other hand, the use of MarkAirs would allow building educational trading card games as in the work by Valente and Marchetti (2015) and have the different tablets enhance the experience by offering associated multimedia contents. Collaborative activities that require discussion, exchange of documents, and gathering of information are another potential use of this platform, since students could sit around a table with their own devices and exchange documents either physically using the markers as the containers of the documents, or by means of a fling gesture to pass the document to another device. The use of the markers as containers would also be interesting in game-based learning scenarios that seek to promote physical exercise, with tablets scattered around a large playground. The children could use the cards to move digital content from one tablet to another distant one.

Acknowledgments

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Chapter 13

Tangibot: A Tangible-Mediated Robot to Support Cognitive Games for Ageing People—A Usability Study

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Abstract

The ever increasing elderly population requires a revision of technology to make it usable and meaningful for them. Most applications take into account their reduced physical and cognitive abilities in order to provide assistive services, but this paper focuses on building technology to improve these capacities through cognitive games. We present Tangibot, a tangible-mediated robot aimed at enabling more intuitive and appealing interactions. A usability study conducted on subjects at three different levels of cognitive impairment (none, mild, and severe) reveals that it is usable and engaging for users with no or mild cognitive impairment, and even though it is less usable for persons with severe impairment, it triggers positive emotional reactions among them, which makes it promising for their use in therapeutic activities.

13.1 Introduction

The number of ageing people in the European Union is increasing rapidly. According to Eurostat (2014), the EU's elderly population is expected to rise from 17.9% in 2012 to 28.1% by the year 2050 due to the increase in average life expectancy and the continuous decline in birth rates. This growth will require adapting existing technological services and creating new ones for this group of people (Nunes et al., 2010).

The idea of ageing people and technology being incompatible is simply a cliché, as has already been shown in the literature. It is not true that the elderly have neither the capacity nor the will to learn and use new technologies. They do have the ability, although not necessarily the necessity (Durick et al., 2013). It would appear that technological devices are normally designed for young people, and neither their purpose nor their interfaces appeal to the elderly. In fact, a study conducted by Fisk et al. (2004) concluded that more than half the problems of this group with technology were associated with usability issues. In particular, the design of input/output devices and user interfaces is critical, as they interact with the user's perceptual and sensorial systems, which, at a certain age undergo changes that may have a negative impact on usability (Carthy et al., 2009; Fisk et al., 2004). These changes include the loss of visual and acoustic capacities, touch- and movement-related issues (arthritis, trembling hands, mobility problems, etc.), and reduced cognitive capacities (Gamberini et al., 2006).

Traditionally, the most common way of interacting with computers were by mouse and keyboard, but these present severe usability issues that can cause the elderly to be reluctant to engage with technology (Torres, 2011). Direct contact via touch interfaces has been shown to be a more suitable alternative for ageing users, since these interfaces present lower cognitive loads and spatial demands, and many efforts are being made of late to make this type of input device more intuitive (Loureiro and Rodrigues, 2011). Torres (2011) proposed using graspable interfaces, which are typically referred to as Tangible User Interfaces (TUIs—Ishii and Ullmer, 1997). These have already been used successfully in cognitive training activities (Sharlin et al., 2004) and offer spatial mapping, input/output unification, and support trial-and-error actions that can exploit innate spatial and tactile abilities, making these interfaces more natural and intuitive.

The present work presents a TUI prototype in the form of a mobile robot controlled by physical paddles aiming at creating games for the elderly to train their cognitive abilities (see Figure 13.1). The proposal consists of a generic and versatile technological device that allows both the elderly and the game designers (therapists) to easily create a range of activities. It also enables natural interactions through tangible manipulations and has the potential to foster socialization and the training of cognitive abilities that can improve the elders' quality of life. Specifically, the contributions of this paper are threefold. First, the design of said platform, called Tangibot; second, a usability study to assess whether the device can be used, and to which extent, by elderly users with different degrees of cognitive impairment; and finally, a discussion about the cognitive capacities that could

Figure 13.1: A user interacting with the platform.

be trained with Tangibot plus some examples of cognitive games that could be developed.

The rest of the paper is structured as follows: Section 13.2 describes related work on technology for the elderly. Section 13.3 presents Tangibot's component parts. Section 13.4 describes a usability study of the technological platform, which is a first step before being able to build cognitive games for the elderly. Section 13.5 contains a description of the cognitive abilities that could benefit from training with Tangibot and some examples of cognitive games. Finally, Section 13.6 contains our conclusions and some ideas for future work.

13.2 Related Works

Many research studies have proposed methods of monitoring elderly people living on their own via ubiquitous devices (ambient or wearable) with minimum impact on their daily activities (e.g., Barsocchi et al., 2015; Lin et al., 2015; Rieping et al., 2014; Zhan et al., 2015). Some focus on tracking the elderly outdoors, such as Lin et al. (2015), who propose a method of detecting when a person gets disoriented when walking on the street, thus being able to provide real-time assistance. Others opt for tracking the elderly in their homes. Zhan et al. (2015), for instance, present a device in the form of reading glasses to classify everyday activities based on what they are looking at and head movements. This system allows people to be tracked by their caregivers and warns them in case of any danger. In a similar fashion, Barsocchi et al. (2015) present an indoor location mechanism that is able to detect deviations from normal behavior.

Other proposals that can be found in the literature also offer technology as a service to the elderly, but in the form of tools to help deal with age-related problems in respect of physical and cognitive capacities. Some of them, in the form of assistive robots or mobile applications (e.g., Goodman et al., 2004; Montemerlo et al., 2002; Otjacques et al., 2009; Shklovski et al., 2004), offer services to improve the quality of life of the elderly and enhance their independence. However, they are often described as aids rather than therapeutic devices to reduce the negative impact of their declining capacities. They are usually designed as personal devices, omitting socialization, even though ageing people seem to assign a high value to socializing and they even report being against technology when it replaces face-to-face interactions (Eggermont et al., 2006). In terms of socialization, efforts have been made to use robots (called assistive social robots—Broekens et al., 2009) to maintain social relations with ageing users. However, they are not intended to foster human-to-human socialization. In fact, some authors have expressed their concerns that these technologies may actually increase social isolation (Sharkey and Sharkey, 2012). As a counterexample, Nostalgia (Nilsson et al., 2003) is a TUI in the form of a textile runner and a radio which enables users to listen to 20^{th} Century music or to old news, which triggers discussion and socialization among the elderly.

In addition to robots, other groups propose the use of digital games (a.k.a., cognitive games) to stimulate declining cognitive abilities and foster socialization (e.g., Carthy et al., 2009; Vasconcelos et al., 2012; Whitcomb, 1990). In this regard, play represents an advantageous way to engage elderly users both cognitively and socially (Gamberini et al., 2006). There are many references in the literature that stress the benefits of videogames for the elderly. They have been proved to decrease reaction times (Clark et al., 1987; Dustman et al., 1992) and improve quality of life, self-confidence, and cognitive skills—the latter two showing a positive correlation (Torres, 2011). Whitcomb (1990) observed that when ageing people played a series of videogames their social interaction improved as did their perceptual-motor capacities (eye-hand coordination, dexterity, fine motor ability, and a reduction of the reaction time). Although the author did not explicitly study how videogames affected cognitive capacities, the study detected a positive effect of videogames on information processing, reading, comprehension, and memory.

Interaction design for videogames for the elderly is a critical dimension to be considered. Whitcomb (1990) enumerates several characteristics that make a videogame unsuitable for them, such as small-sized objects, rapid movements or reactions required, and inappropriate sound. In terms of interaction mechanisms, this study focuses on computer games with interactions mainly transmitted through mouse and keyboard. However, as mentioned in Section 13.1, other interaction mechanisms may be advantageous for the elderly. In this respect, authors such as Jung et al. (2009) explored other input/output devices, e.g., a Wii stick in a game to enhance general wellbeing (physical activity, self-esteem, affection, and level of solitude). However, in our opinion, this type of interaction should be considered with caution when the elderly are involved, as it has been known to produce physical injuries such as tendinitis—or Wiiitis, as it has been called (Bonis, 2007). Alternatively, Chiang et al. (2012) report elderly users significantly improving their visual performance skills through Kinect games. Others have taken advantage of the increasing popularity of handheld devices, which can be moved around and do not require the user to stay in the same position to play (i.e., in front of the television or the computer). MemoryLane (Carthy et al., 2009), although not exactly a game, fosters reminiscence through a PDA application to create "memory stories" with pictures. Vasconcelos et al. (2012) present CogniPlay, a gaming platform running on tablets which includes several games to stimulate cognitive abilities, such as matching pairs to enhance short-term memory and social interaction through competition. de la Guia et al. (2013); de la Guía et al. (2014) also explore cognitive games for the elderly using smartphones and tangibles to increase the engagement of ageing users. However, the consideration of small displays may entail, on the one hand, visualization problems for the elderly. On the other hand, they are usually used as private (single user) devices, which is clearly a step in the wrong direction when collaboration needs to be fostered.

Other works also aim to stimulate either cognitive abilities and/or socialization by taking advantage of the natural and intuitive manipulations that physical (tangible) elements can offer, so that users can focus more on the activity than on controlling the platform. E-CoRe (Kwon et al., 2013) and IntouchFun (Meza-kubo et al., 2010) are two examples of tangible-mediated cognitive games that run on tabletops. The latter also enables remote socialization between the elderly and their families, but this socialization does not take place between several users in the same place. The Virtual Fishing game (Kim et al., 2008) enables co-located experiences in which several users sit next to one another to "fish" in a digital tabletop using a tangible fishing rod, but no cognitive capacities are stimulated. The previous three works rely on tabletops, which nowadays present an elevated economic cost that prevents them from being implanted in many retirement homes. Age Invaders (Cheok, 2010) is an intergenerational game platform that makes use of RFID-enhanced shoes to interact with an interactive floor, and it aims to foster social and physical interaction between elders and their (grand)children, however, it is not suitable for people with limited mobility (e.g., those in a wheelchair), who cannot move around the floor. CurBall (Kern et al., 2006), on the other hand, is another intergenerational game in which ageing users do not need to move. In this work, the players manipulate a virtual ball by physically manipulating a tangible proxy of it. However, this approach also relies on watching a digital element move on a screen, which, as stated above, could cause visualization issues.

Our approach aims to provide both a tangible element to control (a mobile robot) and a tangible way of interacting with it (some physical paddles). Making the interaction usable will enable us to devise games that help the elderly improve their declining cognitive capacities. Ultimately, we would like to build a technological platform that is both appealing to users and that can be used by multiple players at the same time in the same place in order to foster social relationships.

13.3 Technological Platform

The prototype presented in this work consists of two major components: a mobile robot (see Figure 13.2) and a set of paddles as tangible mechanisms to communi-

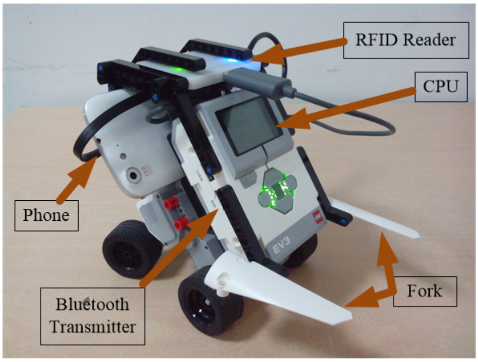

Figure 13.2: Details of the mobile robot.

cate with it (Figure 13.3). Each paddle consists of an extendable stick (maximum length 45cm), which would enable users with reduced mobility to give commands to the robot from a distance by bringing them close to it, without relying on indirect input mechanisms. Also, the use of multiple paddles would allow therapists to design multiuser activities to foster socialization between the participants, in which the different paddles would be distributed among them. To make the paddles more appealing and to visually encode the associated command, they have a distinctive design in EVA foam attached to it via Velcro® strips, which facilitates their replacement. Each figure contains an RFID tag and represents a movement command to the robot, i.e. shift forward (green triangle, as in Figure 13.3-left), stop (red square), turn right (yellow circle), and turn left (blue circle). The use of RFID tags is motivated by their low cost and versatility, since each tag encodes an ID that can be mapped to a specific command for the robot and be easily embedded in the EVA-foam shapes. The robot was constructed using the Lego™ Mindstorms® Ev3 platform, as it is an affordable commercial product and it facilitates rapid prototyping of multiple versions. It communicates by Bluetooth with an external mobile phone connected to an RFID reader. The phone is able to process the RFID tags in the paddles and sends the corresponding movement control commands to the robot. It has an ornamental fork on the front in order to help the users distinguish between the front and back.

Figure 13.4 depicts the communication process between the robot's components when a user gives a certain movement command to the robot. When (s)he brings the paddle close enough to the RFID reader, the RFID tag is read by the phone. The Android application running on the mobile device decodes the id and sends the corresponding command via Bluetooth to the Robot's CPU (i.e., "Forward," "Stop," "Left," and "Right"). Then, depending on the command, the CPU sends the appropriate message to the wheel's motors. When the command is "Forward" or "Stop," both motors move or stop together. When the robot is commanded

Figure 13.3: Extendable robot control paddles. From left to right: shift forward, stop, turn left, turn right.

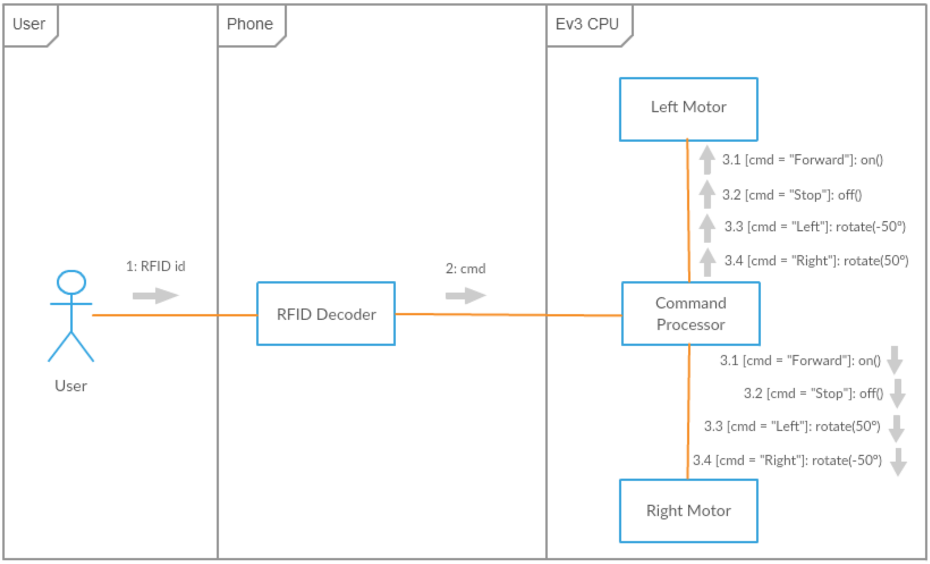

Figure 13.4: Messages sent between the robot's components when a movement command (*cmd*) is sent.

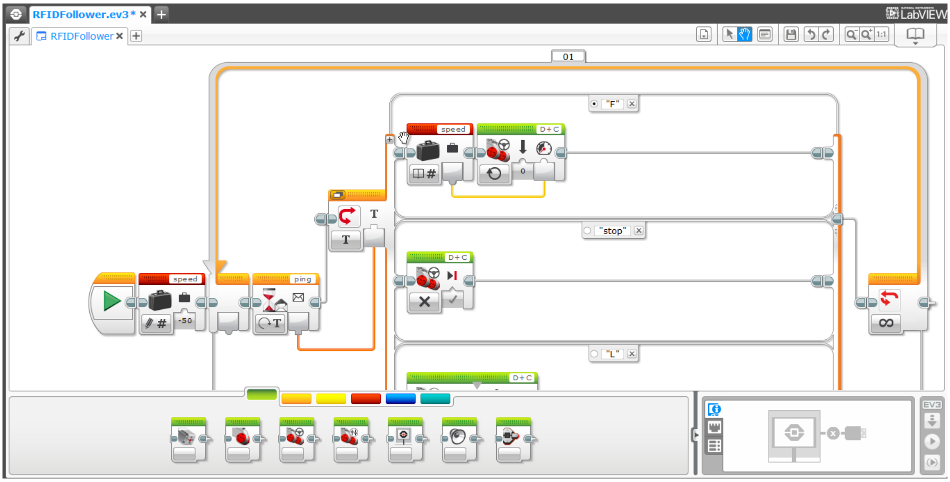

Figure 13.5: Mindstorms™ Ev3 visual programming environment.

to turn, a motor is rotated -50 degrees (backwards) and the other is rotated 50 degrees (forward).

The program running on the robot is coded using the visual programming metaphor of the Lego™ Ev3 platform (see Figure 13.5) which enables the rapid prototyping of different types of movement behaviors.

13.4 Usability Evaluation

Before starting on the design of complex activities or cognitive games for the elderly on this platform, it is necessary to know whether this robot and its TUI are usable and appealing to these people, taking into account the cognitive issues they might have. This section describes an in-lab study conducted with real users with different degrees of cognitive impairment and that consisted basically of controlling the robot's position and orientation with the paddles in order to make it match the corresponding position and orientation of a target.

13.4.1 Apparatus and Participants

Besides the robot and the four paddles, a sheet of paper with a thick black line drawn in the middle was used as a target. The experiment was conducted on a 130×60cm rectangular table (see Figure 13.1).

Forty-six residents of three different retirement homes were asked to participate in this study. Whereas four of them refused even to try and two more quit after the first contact with the platform, the remaining forty agreed to participate until

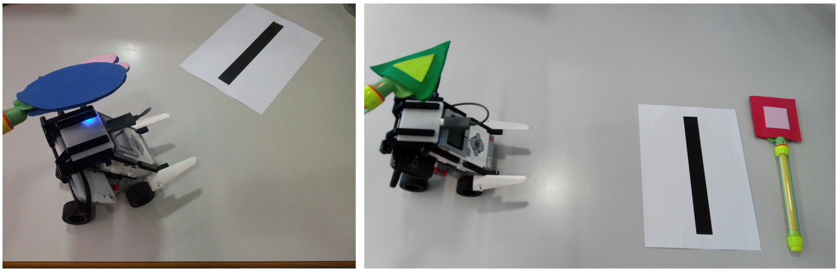

Figure 13.6: Setup for the orientation task (left) and the shifting task (right).

the end of the experiment. Their ages ranged from 57 to 95 years ($M = 81.33$, $SD = 8.48$) and thirty-two were females.

The therapists in charge of the subjects classified them into three groups according to their level of cognitive impairment: none, mild, and severe, regardless of their age. Those with no cognitive impairment were totally independent and capable of reasoning normally. Those diagnosed with mild cognitive issues presented early symptoms of dementia, but were still capable of maintaining a conversation and performing most of their routines. Finally, the ones selected with severe cognitive impairment were unable to maintain a meaningful conversation and their short-term memory was highly defective, although they were still capable of understanding basic instructions. Sixteen subjects had no cognitive impairment, twelve had mild, and twelve others were severely impaired.

13.4.2 Tasks and Procedure

Each user was asked to perform three different tasks: one to control the orientation of the robot, another to shift it from one location to another, and a third as the combination of the first two. Each task was repeated four times. The orientation and shifting tasks required handling only two paddles at a time, and in order to avoid carryover and order effects, they were presented alternatively first and second to each user. The third task was always the combination of the previous ones because it was intrinsically more complex, not only because it required more operations but because it required the users to manage four paddles at a time.

For the orientation task, the target line was situated on an imaginary circumference (with a radius of 30cm) around the robot and pointing towards it at a random angle of between 0º and 360º. The goal was to rotate the robot until it faced the target, as shown in Figure 13.6-left. In the shifting task, the target was situated in front of the robot at a random distance of between 0 and 100 cm, as if it were a finish line (see Figure 13.6-right). In this case, the robot always followed a straight horizontal trajectory and the subjects were instructed to stop it when the robot's fork reached the target's line. For the last task, which combined orientation and shifting, both the robot and the target were placed at random positions on the table and the subjects first had to make the robot face the target and then make it move towards it, as in the previous activities. In all three tasks, after each repetition, the orientation and position parameters were changed. Also, since the concepts of right and left change depending on whether the robot is facing towards or away from the user, after each repetition of a task involving rotation, the robot's initial orientation was alternatively changed from facing the subject to looking away from him.

Each subject performed the three tasks individually seated at the center of the table (see Figure 13.1). Before each task, the subjects were explained the interactions they would have to perform to complete the task, and were given some time to train with the platform until they felt confident enough to begin. For those with communication problems, the supervisor decided when they were ready.

13.4.3 Design

For each task (orientation, shifting, and all combined), the effect of the level of cognitive impairment (none, mild, or severe) was evaluated. The following variables were measured:

- *Proportion of repetitions completed*: For each user, this variable describes how many times (s)he was able to bring the robot to its target orientation and/or position, depending on the manipulation being evaluated.
- *Time:* For those repetitions of tasks that were successfully completed, this variable measures the time the users spent performing interactions until its completion.
- *Unnecessary actions:* If a given repetition of a task was completed, this variable measures the difference between the number of actual actions performed (i.e., turn right, turn left, shift, stop) and the optimal number of actions the task would require, namely, 1 action for orientation tasks (turn left or right continuously till the robot faces the target line), 2 actions for shifting tasks (one to start the movement and another to stop), and 3 actions for the final task in which all the paddles were available (one action to turn, one to start the movement, and a third to stop the robot at its destination).
- *Robot shifting precision errors*: For those tasks when the shifting of the robot was available, this variable indicates the distance between the robot fork and the center of the black target line.
- *Failed actions*: This variable measures the percentage of actions the participants tried to perform and failed by not bringing the paddle close enough to the RFID reader.

Since the administration of questionnaires to obtain subjective feedback was discarded due to the inability of some users to understand the questions, their

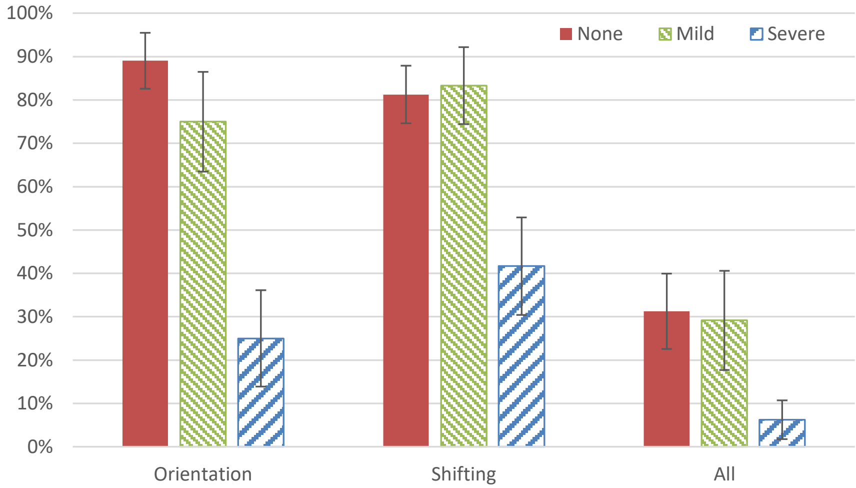

Figure 13.7: Proportion of repetitions completed by subjects with no (none), mild, or severe cognitive impairment (grouped by task).

gestures, reactions, and comments were recorded during the course of the different tasks in order to identify two sets of variables: their impressions of the platform and their different behaviors during the activity.

13.4.4 Results

Proportion of Repetitions Completed

Figure 13.7 shows the proportion of repetitions completed by the users of the different groups for each task. Although the users with no or mild impairment were able to complete most orientation and shifting tasks, this proportion was reduced when they were given all four paddles. An ANOVA ($\alpha = 0.05$) showed a statistically significant effect of the level of impairment on the proportion of repetitions completed, both for the orientation ($F_{2,37} = 12.548$; $p < 0.001$) and shifting ($F_{2,37} = 6.766$; $p = 0.003$) tasks. Post-hoc Bonferroni pairwise comparisons showed subjects with severe cognitive impairment failed to complete significantly more repetitions than those with a lesser degree of impairment ($p < 0.01$), but no significant differences were found in this respect between mild cognitive impairment or none ($p > 0.85$). Since the hypothesis of homoscedasticity did not hold for the task combining orientation and shifting ($F_{2,37} = 5.671$; $p = 0.007$), a Kruskal-Wallis H test ($\alpha = 0.05$) revealed no significant differences between the different levels of impairment on the dependent variable for this task ($\chi^2(2) = 4.958$; $p = 0.084$).

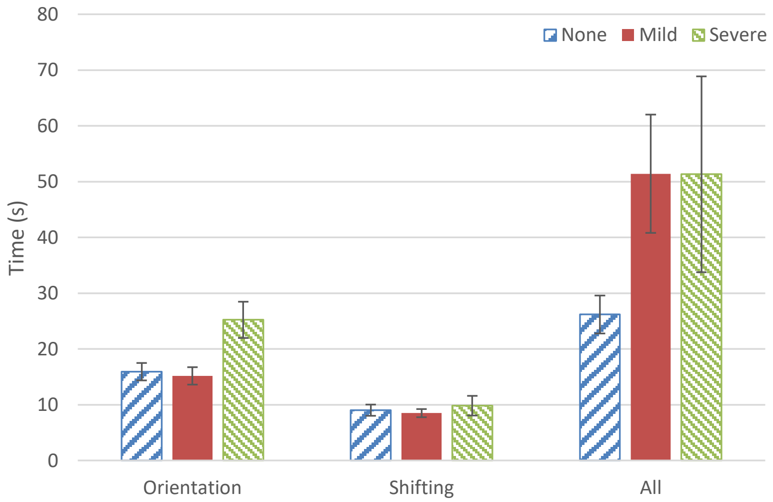

Figure 13.8: Time to complete a repetition of a task by subjects with no (none), mild, or severe cognitive impairment (grouped by task).

Time

As depicted in Figure 13.8, users completed the shifting task faster (∼10s on average), followed by the orientation one (∼20s on average), and the combination of these two was the most time-consuming, in general. An ANOVA ($\alpha = 0.05$) revealed a significant effect of the cognitive impairment level on the orientation task ($F_{2,102} = 4.146$; $p = 0.019$). Post-hoc Bonferroni pairwise comparisons showed that the participants with severe cognitive impairment performed significantly slower ($p < 0.03$) than the rest, although no significant differences were found between those without or with a mild degree ($p = 1.0$). No differences were found either among groups for shifting tasks ($F_{2,109} = 0.273$; $p = 0.762$). With respect to the task in which all four commands were allowed, the hypothesis of homoscedasticity did not hold ($F_{2,34} = 3.368$; $p = 0.046$). Therefore, a Kruskal-Wallis H test ($\alpha = 0.05$) was conducted, which revealed a significant effect of the level of impairment ($\chi^2(2) = 8.479$; $p = 0.014$). Post-hoc pairwise comparisons using a Mann-Whitney U test revealed that the only two groups presenting a significant difference were those with no and mild cognitive impairment ($U = 64.0$; $p = 0.008$), the former outperforming the latter. The ones with severe cognitive impairment presented similar mean completion times to the ones with a mild level.

Unnecessary Actions

As depicted in Figure 13.9, the users performed, on average, less than one extra action to complete the shifting tasks. A few more additional actions were per-

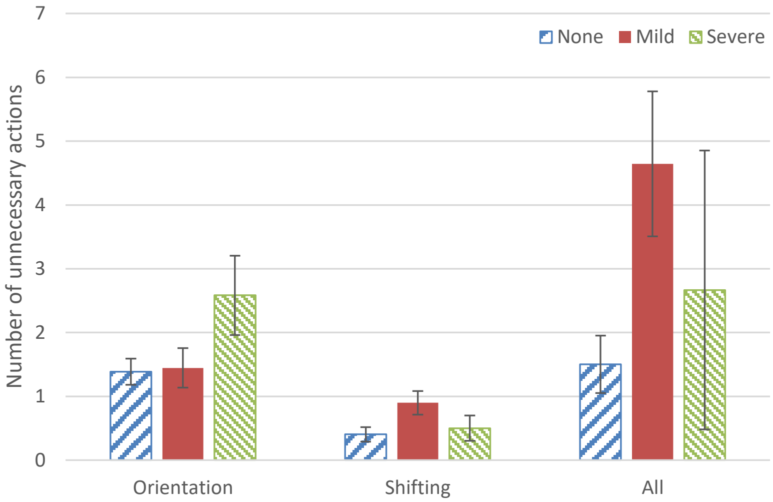

Figure 13.9: Number of unnecessary actions when completing a repetition of a task by subjects with no (none), mild, or severe cognitive impairment (grouped by task).

formed when orientation was allowed (in the other two tasks), but normally no more than 3 or 4. A Kruskal-Wallis H test ($\alpha = 0.05$) showed no significant effect of the impairment level on the dependent variable for both orientation and shifting tasks ($p > 0.05$). However, it did reveal a significant effect for the tasks using all four paddles ($\chi^2(2) = 7.409$; $p = 0.025$). Post-hoc Mann-Whitney U tests revealed the subjects without cognitive issues performed significantly fewer unnecessary actions than the ones with mild cognitive impairment, but no differences were found between these two groups and the one with severe impairment, probably because of the high dispersion of the data, as depicted in Figure 13.9, which indicates that the participants with severe cognitive issues presented either very few unnecessary actions or many ($\sim$5).

Robot Shifting Precision Errors

As depicted in Figure 13.10, the users were able to stop the robot relatively close to the target (normally at less than 10cm) in both tasks in which shifting was available. Although an ANOVA ($\alpha = 0.05$) did not find any significant differences between levels of cognitive impairment for the task with all four paddles ($F_{2,34} = 0.335$; $p = 0.718$), it did reveal a significant effect of this factor on the shifting task ($F_{2,109} = 4.382$; $p = 0.015$). Post-hoc Bonferroni pairwise comparisons revealed that the group with severe impairment was significantly less precise ($p < 0.05$) when trying to stop the robot at a specific point.

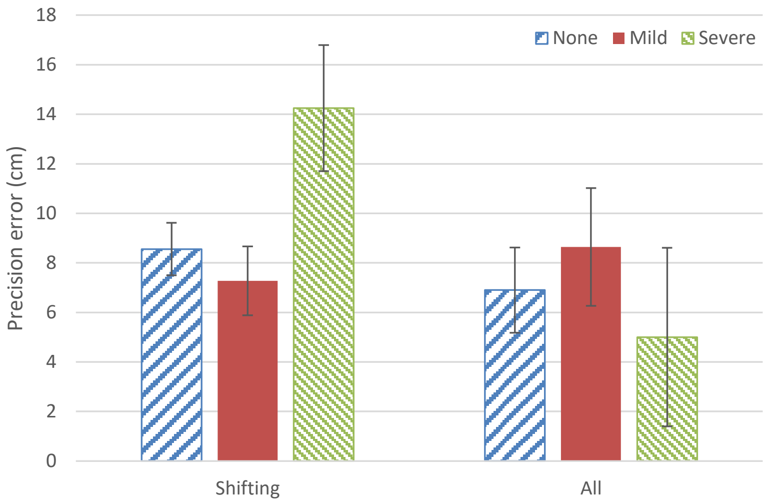

Figure 13.10: Shifting precision errors measured as the distance to the target when completing a repetition of a task by subjects with no (none), mild, or severe cognitive impairment (grouped by task).

Failed Actions

Figure 13.11 depicts the proportion of times the participants tried to give a command to the robot and failed because they did not bring the paddle close enough to the robot's RFID reader. A Kruskal-Wallis H test ($\alpha = 0.05$) was performed on this variable and showed a significant effect of the subjects' level of cognitive impairment ($\chi^2(2) = 29.4$; $p < 0.001$). Post-hoc Mann-Whitney U tests revealed the users with severe cognitive issues making significantly more failed actions ($p < 0.001$) than the rest, yet it was, on average, 10.33% ($SD = 0.184$). No significant differences were found between the participants with no or mild cognitive impairment ($U = 10856.0$; $p = 0.958$), whose actions were almost always successful.

Observational Findings

The users' impressions with regard to the platform were analyzed, and are summarized in Table 13.1 for each level of cognitive impairment. After completing the task, they were asked directly about whether they had liked the platform, and 32 out of 40 (80%) answered affirmatively. However, the researchers noticed in some cases their answers did not seem sincere, maybe because they did not fully understand the question and/or they were trying to be polite. Instead, their spontaneous comments and reactions were observed during the session and subsequently analyzed. In this respect, 25 out of 40 users (62.5%) showed clear manifestations of enjoyment, although these were more frequent in users as they

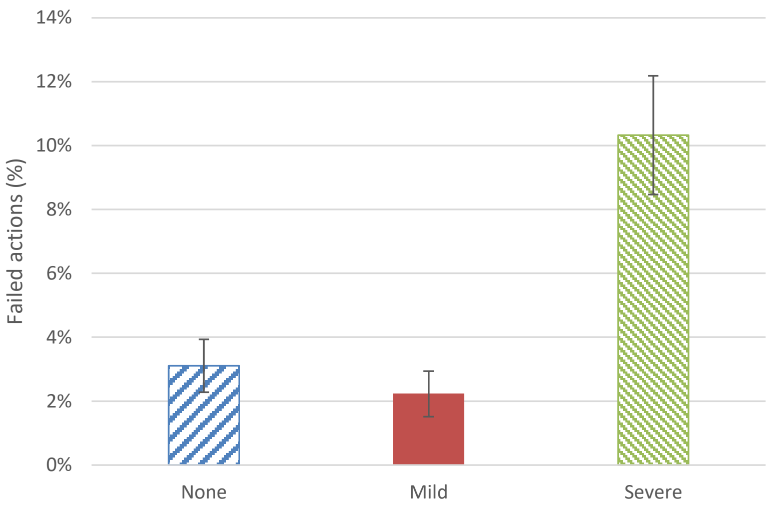

Figure 13.11: Percentage of actions that were not successful at giving a command to the robot (grouped by level of cognitive impairment).

Table 13.1: Number (and proportion) of users with each level of cognitive impairment that expressed the specified impressions.

Impression	**None (out of 16)**	**Mild (out of 12)**	**Severe (out of 12)**	**Total (out of 40)**
Report liking the platform	15 (93.75%)	9 (75%)	8 (66.67%)	32 (80%)
Manifest enjoyment	12 (75%)	7 (58.33%)	6 (50%)	25 (62.5%)
Found it entertaining	2 (12.5%)	2 (16.67%)	1 (8.33%)	5 (12.5%)
Do not want to stop playing	3 (18.75%)	2 (16.67%)	4 (33.33%)	9 (22.5%)
Cannot wait for the next repetition	4 (25%)	1 (8.33%)	2 (16.67%)	7 (17.5%)
Praise the robot's beauty	7 (43.75%)	2 (16.67%)	4 (33.33%)	13 (32.5%)
Express contempt	0	1 (8.33%)	3 (25%)	4 (10%)

Table 13.2: Number (and proportion) of users with each level of cognitive impairment that showed the specified behaviors.

Behavior	**None (out of 16)**	**Mild (out of 12)**	**Severe (out of 12)**	**Total (out of 40)**
Need help at some point	10 (62.5%)	5 (41.67%)	8 (66.67%)	23 (57.5%)
Start with the closest paddle	6 (37.5%)	1 (8.33%)	2 (16.67%)	9 (22.5%)
Plan in advance	3 (18.75%)	4 (33.33%)	0	7 (17.5%)
Discover many ways to stop	4 (25%)	2 (16.67%)	0	6 (15%)
Talk to the robot	3 (18.75%)	1 (8.33%)	1 (8.33%)	5 (12.5%)
Cheat	2 (12.5%)	0	2 (16.67%)	4 (10%)

presented lower cognitive impairment. They either laughed or expressed directly they were enjoying the activity. Concretely, of these 25 users, 20% of them found it entertaining ("It's very funny!," "it's super-fun!," "this is great!"), 36% did not want to stop playing ("I could spend all day playing with this little robot," "we have to stop already? Now that I was getting a taste for it..."), and 28% could not wait for the next repetition of the task to be set up and did not stop giving the robot commands. Besides, four users that were reluctant to use it at first because they thought they "could not do it right," ended up having fun with it (and two of them did not want to stop in the end). Furthermore, 13 out of 40 participants (32.5%) found the robot "nice," "pretty," or "astonishing," and were the ones with mild cognitive impairment who expressed less comments about it. Nevertheless, 4 out of 40 (10%) expressed clear impressions of contempt and irritation during the task. They found it "silly" and "useless." In this respect, one of them claimed: "What dumb things they do nowadays..." These expressions were more frequent among participants with severe cognitive impairment.

Other observations made during the experiment concerned the behaviors that emerged during the interactions, and are summarized in Table 13.2 for each level of cognitive impairment. Many users (57.5%), regardless of their level of cognitive impairment, needed help at some point to complete the tasks if they forgot what they were doing or which paddle represented which command. This help provided by the researchers or the therapists consisted of reminding them to bring the robot to match the target's position and/or orientation if they noted some distraction on the subject, and telling them what paddle entailed which movement in case the participant asked. In no case was the solution to the task revealed. It was also observed that 9 out of 40 (22.5%) users usually started the interaction with the paddle they already had in their hands or whichever was closest, and only 7 (17.5%) planned in advance which interactions to perform. Another remarkable behavior observed was that during the task with all four paddles, 6 users (15%) discovered that they could stop the robot not only with the red-squared paddle, but also with those for turning, and then put aside the former, so that they would have to handle fewer paddles at once. It is worth noting that no user with severe cognitive impairment was able to plan in advance nor discovered the alternative way of stopping the robot. Some other minor findings were: 5 users (12.5%) reinforced their manual commands with words by talking to the robot, and 4 participants (10%), none of which had a mild cognitive impairment, cheated at some point by moving the robot with their hands or bringing the target to the robot. We consider they cheated and not simply were confused or did not understand the task because when they did they naughtily laughed about it.

13.4.5 Discussion

The previous results indicate that Tangibot is usable by ageing people with none or mild cognitive impairments but is too demanding for those with severe cognitive impairments. In general, the participants with none or mild cognitive impairments were able to complete most of the exercises presented to them that required the use of two paddles at a time (i.e., the orientation and shifting tasks), and within a reasonable time. When handed the four paddles to make the robot both rotate and shift towards a target, the number of repetitions they were able to complete was considerably reduced (with mean success rates of 31.25% for the participants without impairment, and 29.17% for the ones with mild issues), and needed more time for those they did perform (mostly when they presented a mild cognitive impairment). This could be explained by this kind of task being cognitively more complex since they could not hold all four paddles in their hands at once and had to remember and manage more commands. As explained in Section 13.4.4 (Observational Findings), this is why 15% of the users discarded some paddles when they found they could achieve similar results with the other ones (i.e., the stop action was included as a pre-action in the paddles for turning right or left). These results suggest that, in order to design future cognitive games with this platform, a single user should handle at most two commands at once. Multi-user activities could be built in which two or more users had to collaborate to solve a problem by jointly controlling the robot (each one being in charge of one or two paddles). This way we could foster not only the development of cognitive abilities but also socialization among peers.

As Figure 13.12 depicts, when a user was unable to successfully complete a given repetition of a task, it was due to three main reasons: inactivity (i.e., remaining still not knowing what to do), aimlessness (i.e., interacting with the robot without a clear goal, making it move arbitrarily), and fall (i.e., not being able to stop the robot before falling off the table, where the researcher had to intervene and grab it). During the task where the users controlled the orientation of the robot only, the main reason of incompletion was aimlessness, since the robot could not fall off the table. However, the more cognitive impairment the subjects had, the more cases appeared when they remained inactive in front of the robot not knowing how to proceed with the interaction. For shifting tasks, the most common reason for not being able to complete a repetition was a fall, because they made it move and kept staring at it idly. Surprisingly, all the users presented the same reasons in the same proportions regardless of their level of impairment. During the final task in which they handled all the paddles, the three previous reasons

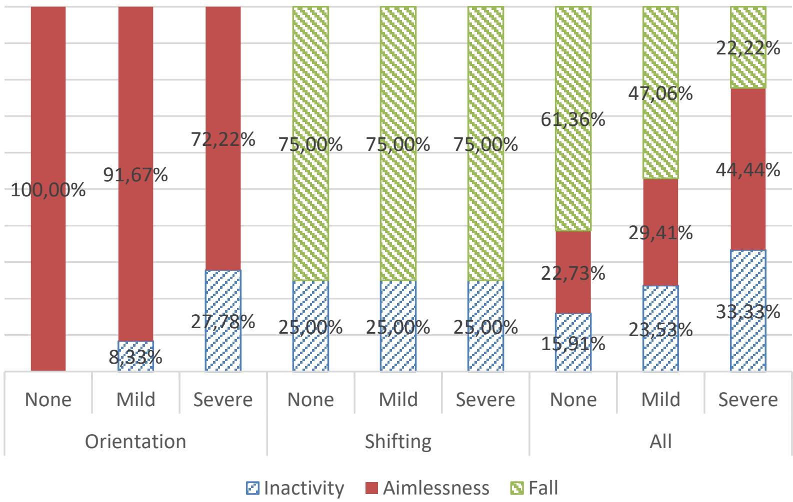

Figure 13.12: Reasons to not being able to complete a repetition of a task (grouped by task and level of cognitive impairment).

occurred. As they had more sever cognitive impairment, the robot falling off the table gave way to aimlessness and inactivity.

The subjects with none or mild cognitive issues also achieved a fair degree of precision in terms of a reduced number of unnecessary actions and a small distance between the robot and the target when making the former move towards the latter. With respect to the number of extra actions performed, however, the users performed a few more in the orientation than in the shifting task. This occurred because, in some cases, they confused directions, and did not understand why, using the same paddle, the robot sometimes turned to their right when it was looking at them and sometimes to their left when it was facing in the opposite direction. During the shifting task they were more accurate in this respect. This could be due to them finding the interaction more intuitive, since they were able to complete, on average, more than 80% of the repetitions. As happened with the time to complete the task, when they were handling all four paddles, the subjects with mild cognitive impairment performed significantly more unnecessary actions than those without impairment, probably because they needed more trials to fully understand the task. Nevertheless, in general terms, having a mild cognitive impairment seems not to be a hindrance to using this platform.

Elderly people with severe cognitive issues were significantly less successful in completing the tasks than the ones with none or mild impairments. In the task where orientation and shifting were combined, however, the statistical analysis did not reveal a significant effect of the cognitive impairment level, although the users with a severe one presented lower mean values of the number of completed tasks (6.25% versus 31.25% and 29.17%). Nonetheless, in the orientation and shifting tasks, where they only had to handle two paddles at once, the analysis of several variables indicates the worse performance of these users. For example, they spent significantly more time and performed more unnecessary actions on average than the other two groups, rotating the robot in the orientation task, but no differences were found in the shifting task. This is probably because the former required them to be more precise in order to consider the task completed (i.e., they had to make the robot look at the target), which entailed correcting their actions if they missed the target, whereas the shifting task was considered successful even if the robot stopped without precision after the "finish line" was crossed. This reason is supported by the significantly higher shifting precision errors in the shifting task with respect to the other groups of users. Moreover, the subjects with a severe impairment presented significantly more failed actions because they could not fully understand and/or remember where they needed to put the paddle for the robot's RFID reader to detect it.

To sum up, from a quantitative perspective, it can be concluded that Tangibot would probably be more suited to subjects with none or mild cognitive impairments. According to their personal preferences, the less cognitive impairment they presented the more they seemed to like the platform as well (both by expressing more enjoyment and less contempt). However, regardless of the cognitive issues, 62.5% of the users showed clear manifestations of enjoyment when interacting with the robot, which indicates that the platform could be a useful tool for triggering positive emotional reactions even in the case of persons with severe cognitive impairments (50% of them showed positive manifestations). Even in cases in which some users were reluctant to engage in the activity because they were afraid they could not perform well, they finally ended up having a good time. During subsequent discussions with the therapists, they stated that many users (mostly the ones with none or mild impairments) talked among themselves about the experience with Tangibot, and some of them, after completing the task, went running to their families to tell them how they had been handling something so complex as a robot and how well they had performed. Many elderly participants told us their grandchildren would "love" such a platform as well. For this reason we believe that intergenerational activities with Tangibot could be worth exploring in the future.

13.4.6 Threats to Validity

There are some limitations in our study. On the one hand, the small proportion of repetitions completed by the users with severe cognitive impairment in the task where all four paddles were available (6.25% on average) has resulted in high standard deviation of the data and, as a result, a lack of statistical power, which has complicated the comparison between those participants with severe issues and the other two groups of users for some dependent variables: time and unnecessary actions.

On the other hand, as pointed out by Glisky (2007), it is important to note that deficits in perception (visual, acoustic, etc.) have a significant impact on cognition, therefore they could also have an impact on the usability of Tangibot. In our study we have not taken into account these perceptual impairments and have only classified the users with respect to the level of cognitive impairment, a complementary study would be necessary to check the possible effects of perceptual deficits on the usability of our platform.

13.5 Designing Cognitive Games for Ageing People with Tangibot

13.5.1 Age-Related Reduction of Cognitive Abilities

According to Glisky (2007), there are three basic cognitive functions that diminish with age and could be trained:

- *Attention*: It spans across virtually all other cognitive domains, except when the task at hand is automatized. There are two types of attention that are affected by age: selective and divided. Whereas the former consists on being able to focus on some stimuli while filtering out other irrelevant ones, divided attention requires processing multiple sources of information or performing multiple tasks at the same time.

- *Working memory*: It is probably the main source of age-related deficits that has an impact in many other cognitive domains such as language, problem solving, and decision making. It involves the active manipulation of information that is currently being maintained in the task at hand.

- *Long-term memory*: It requires the retrieval of information that is no longer present or being maintained in an active state. It is also composed of several subtypes, but the ones specifically affected by normal ageing are the following: episodic memory (i.e., being able to remember personally experienced events in a specific place at a particular time), and prospective memory (i.e., remembering to do things in the future) when no reminders in the environment are available (e.g., remembering when to take a specific medication).

In addition to those basic functions, Glisky also distinguishes other, higher-level, cognitive capacities which become affected by ageing. Some of them, e.g., language or decision making, are not reduced per se on the elderly, but they are affected by working memory loss. On the other hand, she identifies executive control as a high-level cognitive function that is indeed a "primary contributor to cognitive decline with age." Executive control is "a multi-component construct that consists of a range of different processes that are involved in the planning, organization, coordination, implementation, and evaluation of many of our routine activities."

Finally, there are other cognitive functions that according to Glisky are not necessarily affected by ageing such as sustained attention (i.e., being able to maintain concentration over an extended period of time), semantic memory (i.e., remembering factual facts, words, and concepts), autobiographical memory (i.e., memories about oneself), procedural memory (i.e., the knowledge of skills such as riding a bicycle), and implicit memory (which refers to "a change in behavior that occurs as a result of prior experience, although one has no conscious or explicit recollection of that prior experience"). Although some of these (procedural and implicit memory) probably could not be trained using our platform, the remaining ones could also be trained by designing cognitive games with Tangibot.

13.5.2 Examples of Cognitive Games

Several studies (e.g., Baltes et al., 1989; Rogers, 2000; Smith et al., 2009) as well as some therapists from the retirement homes where the experiment described in Section 13.4 took place remarked the importance of training cognitive abilities in the elderly in order to prevent or slow down their decline over time. Given the good acceptance of Tangibot among the participants, we consider it a motivating element for older people to engage in cognitive games that help them train such capacities. Four generic samples of such games are explained below, classified by the main cognitive capacity they are designed to train. All of them have the same basic idea: control the robot's movements with the paddles in order to make it either follow a path or reach a destination.

Selective Attention

This game would consist on the adaptation of the "visual search" activity, a classic to train selective attention (Glisky, 2007). The therapists would place a target image on a table, and around it, they would arrange a bunch of other images acting as distractors. Selective attention is trained in this activity since users would need to filter out the distractors and locate the target image. What they should do is make the robot move and make it stop on top of the target image. The complexity of the task could be increased by augmenting the number of distractors or by making them more similar to the target. According to Rogers (2000), the selective attention depends on the familiarity of the user with the presented objects. Taking this into account, in a low complexity level the images to memorize could be easily recognizable by the participants, and the game could be made more challenging by introducing pictures of objects they are not familiar with.

Working Memory

Working memory is trained intrinsically with Tangibot since users have to remember which paddle entails which command to the robot. However, a game example to train working memory could be to arrange several images on a table for the user to memorize where each one is (as shown in Figure 13.13). Next, the therapist would turn them upside down, and then ask the user to bring the robot to one of them. The complexity could be increased by adding more images for the user to remember or by making him/her bring the robot to many targets.

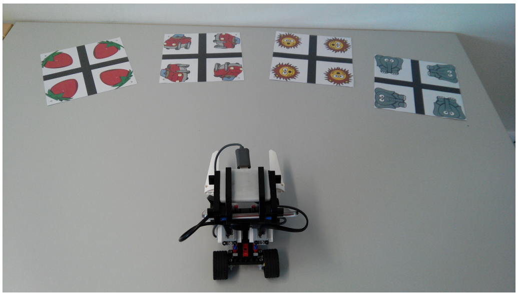

Figure 13.13: Example of a cognitive game to stimulate working memory with Tangibot.

Another game to train working memory could consist of the therapist drawing multiple paths on the table, then making the robot follow a specific path, and, finally, having the players make the robot repeat that trajectory. The complexity in this case could be increased by adding more possible paths for the user to choose from or by making them longer.

Episodic Memory

In a similar way to Carthy et al. (2009), a storytelling activity could be designed in order to foster reminiscence. In our context, several pictures of the user's life could be placed in a chronological order on the table. Then, the user would have to bring the robot to one of them and, when on top of it, (s)he would have to talk about what they remember of the moment that photo represents. The therapist could increase the difficulty by presenting the images unsorted for the user to visit in the correct order. Also, this task could be used to train selective attention by adding some meaningless pictures, which the user would have to avoid.

Prospective Memory

The therapist would arrange (unsorted) several images on the table from the user's daily routine, for example, representations of the meds (s)he needs to take during the day. Then, in a similar way as the previous game to foster episodic memory, the older participant should visit all images in the correct order. The images could represent any succession of tasks the users need to conduct, and the complexity of the game can also be increased by adding more stimuli, either meaningful or not (if selective attention wants to be trained).

Stimulating Other Capacities

Besides the specific cognitive abilities the four previous games are designed to train, since they make use of Tangibot other capacities can be stimulated. For ex-

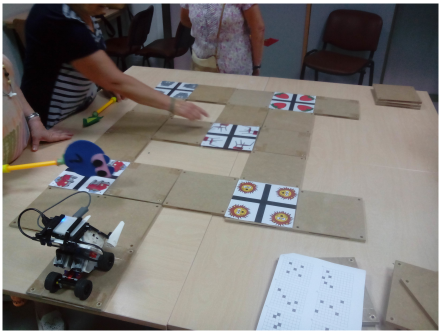

Figure 13.14: Four users playing a game to foster creativity with Tangibot.

ample, executive control is exercised because controlling the robot requires certain planning and coordination of actions. Also, divided attention is trained since users need to focus on controlling the robot at the same time as they need to complete the game's task.

Another important aim of this platform is avoiding the dangers of social isolation that could provide a similar implementation where each user would hold a tablet or be in front of a computer screen. As suggested by the results of Section 13.4.4, each user should not be in control of more than two paddles at a time. Therefore, there should be devised collaborative scenarios where several people situate around the table and help one another find better solutions, and/or simply discuss the game and the situation themselves. Also, since some users felt proud of their performance (see Section 13.4.5), in our opinion, these activities using Tangibot could also foster self-confidence in older adults.

Not only could Tangibot be used to train cognitive abilities and foster socialization. In our opinion, it could also be used in the context of physical rehabilitation or exercising. The mechanism to control the robot with the paddles trains coarse motor skills. Fine motor skills could also be stimulated by making the robot rotate and move to a specific target with precision. For those users able to walk, a therapist could draw a path and the users would have to make the robot follow it by walking by its side.

Putting It All Together

Tangibot could also be used to build more complex games that integrate the training of several cognitive and physical abilities. For example, we have already prototyped a collaborative game to foster creativity. In this case, the therapist places several images on the table. Then, the users need to build a path by putting some wooden tiles together that connects all the images in order to, finally, make the robot visit all the images by walking on top of the wooden path (see Figure 13.14). After having completed this task, they would be asked to repeat the process by finding different paths to solve the same problem, thereby promoting creativity. Besides, this game would also train coarse and fine motor skills (because the robot could not leave the wooden path), and it would also stimulate collaboration (since each user would be in charge of a paddle and all together should come up with a solution to the problem), executive control in the form of planning and coordination, divided attention (since they would be conducting several operations at the same time), working memory (not to repeat a path defined previously), and selective attention (because they would be encouraged to make the solutions as optimal as possible, hence requiring them to discard irrelevant paths). A preliminary test was made with real users, in which we found the users to effectively socialize, find different solutions, and have fun. These preliminary findings illustrate the versatility of Tangibot and make this specific activity a promising area for future work.

13.6 Conclusions

In this paper we present a prototype of Tangibot, a mobile robot mediated by four tangible paddles, which is a platform for constructing cognitive games for the elderly. The design would not only be able to foster human-to-human socialization but also the tangible capabilities would bring more natural and intuitive interactions that would appeal to ageing users. The platform is built of cost-effective materials, and its design allows for a quick setup and high versatility and scalability.

We conducted a study with 40 subjects and concluded that Tangibot is generally usable by older adults with none or mild cognitive impairments. The study also revealed that it may be too complex for those with severe cognitive issues. However, regardless of their cognitive impairments, the platform was found to be appealing to most participants, which, in our opinion, would make Tangibot a promising technological device that could serve as a motivating technological artifact in games to foster cognitive abilities. Our study also revealed that elderly players should only handle two paddles at most, which would enable the construction of multi-player games in which each player would be in charge of giving a movement command to the robot.

We have also provided several examples of games to train the cognitive capacities, and have also glimpsed the design of a more complex game aimed at stimulating many of these abilities, plus some physical ones and other higher-level capabilities such as creativity.

As future work, additional experiments would be conducted in order to study the positive effect of the platform on the already enumerated capacities meant to be stimulated. We will delve deeper into the usability of Tangibot by checking the possible effects of users' gender, specific cognitive impairments, and, as mentioned in Section 13.4.6, perceptual deficits. Also, in order to take advantage of the smartphone in the platform, we will consider augmenting the experience with Tangibot by providing visual and acoustic feedback to the users; for example, by providing visual and audio clues to help users with acoustic and visual issues, respectively. Additionally, we plan to exploit the capabilities of RFID technology by embedding tags in other common objects and study the impressions of ageing people towards interacting with the robot via those other elements. Finally, we will also explore the game described in Section 13.5.2 (Putting It All Together) to foster creativity, and, since Tangibot has already been found usable for young children in another study (Garcia-Sanjuan et al., 2015d), different scenarios will be examined in which the platform is used conjointly by elders, young adults, and children to foster intergenerational activities.

Acknowledgments

This work is supported by Spanish Ministry of Economy and Competitiveness and funded by the European Development Regional Fund (EDRF-FEDER) with Project TIN2014-60077-R. It is also supported by fellowship ACIF/2014/214 within the VALi+d program from Conselleria d'Educació, Cultura i Esport (Generalitat Valenciana), and by fellowship FPU14/00136 within the FPU program from Spanish Ministry of Education, Culture, and Sport.

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Chapter 14

Augmented Tangible Surfaces to Support Cognitive Games for Ageing People

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Abstract

The continuous and rapidly increasing elderly population requires a revision of technology design in order to devise systems usable and meaningful for this social group. Most applications for ageing people are built to provide supporting services, taking into account the physical and cognitive abilities that decrease over time. However, this paper focuses on building technology to improve such capacities, or at least slow down their decline, through cognitive games. This is achieved by means of a digitally-augmented table-like surface that combines touch with tangible input for a more natural, intuitive, and appealing means of interaction. Its construction materials make it an affordable device likely to be used in retirement homes in the context of therapeutic activities, and its form factor enables a versatile, quick, and scalable configuration, as well as a socializing experience.

14.1 Introduction

The number of ageing people in the European Union is fiercely increasing. According to Eurostat's statistics (2014), EU's elderly population is expected to rise from 17.9% in 2012 to 28.1% by the year 2050 due to the average increase of life expectancy and the continuous decline in birth rates. This growth will require adapting existing technological services and creating new ones for this group of people (Nunes et al., 2010).

The idea of ageing people and technology being incompatible is a cliché, as it has been already proven in the literature. It is not true that the elderly have not the capacity or the will to learn and use new technologies. They do have the ability, although not necessarily the necessity (Durick et al., 2013). It would appear that, traditionally, technological devices have been designed for youngsters, and neither their purpose nor interfaces are appealing to ageing people. In fact, a study conducted by Fisk et al. (2004) concluded that more than half of the problems that elders experience with technology were associated with usability issues. In particular, the design of input/output devices and user interfaces is critical because they interact with the user's perceptual and sensorial system, which, at certain age, experience some changes that may have a negative impact on usability (Carthy et al., 2009; Fisk et al., 2004). Examples of these changes are decrease of visual and acoustic capacities, touch- and movement-related issues (such as arthritis, tremors, walking problems, etc.), and a reduction of some cognitive capacities (Gamberini et al., 2006).

Traditionally, the most common ways of interacting with computers were using mouse and keyboard, but these present severe usability issues that can cause the elderly to be reluctant to engage with technology (Torres, 2011). Direct contact via touch interfaces, instead, has shown to be more adequate to ageing users since these interfaces present less cognitive load and less spatial demand, and many efforts are being made as of late in order to create more intuitive user experiences using this kind of input devices (Loureiro and Rodrigues, 2011). Furthermore, Torres (2011) proposes to devise alternative ways of performing input, for example, via tangible interfaces, which are typically referred as Tangible User Interfaces or TUIs (Ishii and Ullmer, 1997). These offer spatial mapping, input/output unification, and the support of trial-and-error actions that can exploit innate spatial and tactile abilities; and have already been used successfully in cognitive training activities (Sharlin et al., 2004).

The present work contributes to the field with a TUI prototype in the form of a table-like surface aiming at building games for the elderly to train their cognitive abilities (see Figure 14.1). It intends to be usable by providing a scalable and versatile means of configuration for both ageing people and the therapists who design the games, and by enabling a more natural interaction through tangible manipulations along with fully supporting touch interactions. Another important purpose of our proposed infrastructure is to foster socialization and the training of cognitive abilities that can improve elders' quality of life. The rest of the document is structured as follows: First, related work on technology for the elderly is

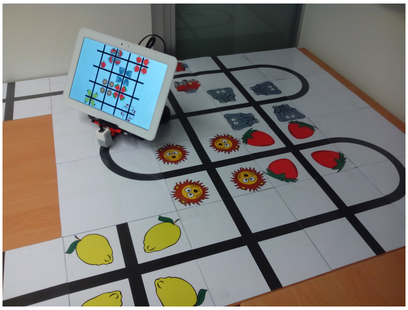

Figure 14.1: Example of a game running on the surface.

described; then, our augmented tangible surface is presented; section 14.4 explains how our prototype could be used to build games for elders' cognitive training; and, finally, future work and conclusions are drawn.

14.2 Related Works

Many research works have proposed technology to help ageing people deal with age-related problems in respect of physical and cognitive capacities. Some of them, in the form of assistive robots or mobile applications (e.g., Goodman et al., 2004; Montemerlo et al., 2002; Otjacques et al., 2009), offer services that improve the quality of life of the elderly and enhance their independence. However, they are often devised as aiding tools and not as therapeutic mechanisms to reduce the negative impact of their decreasing capacities. Besides, they are usually designed as private devices, omitting socialization, despite ageing people seem to assign a high value to socialization and they even report being against technology when it replaces face-to-face interactions (Eggermont et al., 2006). In terms of socialization, there have been efforts using robots, called assistive social robots (Broekens et al., 2009), focusing on improving socialization between themselves and ageing users. However, they do not intend to foster human-to-human socialization. In fact, some authors have expressed their concerns about these technologies incrementing social isolation (Sharkey and Sharkey, 2012).

In addition to robots, other works propose the use of digital games (a.k.a. cognitive games) that stimulate the previously mentioned decreasing cognitive abilities, and also foster socialization (e.g., Carthy et al., 2009; Vasconcelos et al., 2012; Whitcomb, 1990). In this sense, playing represents an advantageous way to engage elder users both cognitively and socially (Gamberini et al., 2006). There are many references in the literature stressing the benefits of playing videogames for the elderly. They have been proved to decrease reaction times (Clark et al., 1987; Dustman et al., 1992), and improve quality of life, self-confidence, and cognitive skills—these two showing a positive correlation (Torres, 2011). Moreover, Whitcomb (1990) analyzed how ageing people played a series of videogames, and observed that they increased social interaction and perceptual-motor capacities (eye-hand coordination, dexterity, fine motor ability, and a reduction of the reaction time). Also, although the author did not explicitly study how videogames affected cognitive capacities, the study detected a positive effect of videogames on information processing, reading, comprehension, and memory.

Interaction design for videogames targeting elder people is a critical dimension to be considered. Whitcomb (1990) also enumerates several characteristics that make a videogame unsuitable for them, such as small-sized objects, rapid movements or reactions required, or the sound being inappropriate. In terms of interaction mechanisms, this study focused on computer games, which are mainly interacted through mouse and keyboard. However, other interaction mechanisms, as we discussed in the previous section, may be advantageous when considering ageing people. In this respect, authors such as Jung et al. (2009) have explored other input/output devices, e.g. a Wii stick in a game to enhance general well-being (physical activity, self-esteem, affect, and level of solitude). However, in our opinion, this type of interaction should be considered with caution when the elderly are involved because it has been reported to produce physical lesions such as tendinitis—or Wiiitis as it has been called (Bonis, 2007). Alternatively, Chiang et al. (2012), through Kinect games, report elder users improving significantly their visual performance skills. Others, however, have taken advantage of the increasing popularization of handheld devices. MemoryLane (Carthy et al., 2009), although not exactly a game, fosters reminiscence through a PDA application to create "memory stories" with pictures. Vasconcelos et al. present CogniPlay (2012), a gaming platform running on tablets which includes several games to stimulate cognitive abilities, such as matching pairs to enhance short-term memory, and social interaction through competition. However, the consideration of small devices or elements that are designed to be used by a single user is clearly a step in the wrong direction when collaboration needs to be fostered.

Our approach intends to merge touch interaction capabilities provided by handheld devices such as tablets but at the same time taking advantage of the natural and intuitive manipulations that physical (tangible) elements can bring. Moreover, by proposing a surface-like configuration with such affordable materials and devices, a cost-effective public space can be built where elder players can all have a simultaneous and equal access to the game space which fosters collaboration.

14.3 Designing the Prototype

The prototype presented in this work aims at supporting collaborative therapeutic games for the elderly around physical tables. Current digital tabletop technology would indeed allow us to deliver fine-grained touch interactions and high-end visual representations, but fully interactive tabletops are still expensive, and their form factor complicates their mobility and scalability. Instead, we propose a cost-effective way of creating a surface by arranging physical tiles, which can form a

Figure 14.2: The tangible surface's parts. On the left, the different tiles that compose the physical surface. On the right, the mobile robot that displays the digital content.

table-like interactive 2D environment of any arbitrary topology anywhere on a flat terrain. The resulting surface becomes a public space where all users can collaborate in problem solving tasks, and therapists can design cognitive games, such as matching pairs to train short-term memory, simply by handling the physical tiles, without any technological knowledge required. This type of surface is digitally augmented in order to provide richer features to the games. However, to decrease the decoupling between the physical and the digital space that would take place if the digital information was shown in a separate display held by the players, a tablet is instead mounted on a small mobile robot that moves through the physical surface displaying digital contents within the context of the physical space (see Figure 14.1). With respect to the input mechanisms supported for the elder participants, they can both use touch contacts and gestures on the tablet, and interact directly with the physical surface by adding and removing tiles that have a specific digital behavior associated or by giving commands to the robot using special physical tags, hence providing a more natural and intuitive interaction.

Our augmented tangible surface consists of two major components, as can be seen in Figure 14.2. The 2D surface can be constructed by arranging several 20×20cm tiles following any desired flat configuration. Each tile has a number of black lines which allow the robot to move in the physical space in different directions by following them. The lines may represent a crossroads for the robot to choose which direction to take, or a specific path such as a curve. Depending on the game, each tile may also contain some drawings that make sense to the users in the context of the activity being developed. As Figure 14.3 (left) depicts, each tile consists of a squared piece of paper with the path black lines and possibly the drawings, an RFID tag to be read by the robot when passes over it and which provides the tablet with digital information, another piece of paper with only the path printed (representing the back of the tile), and two pieces of plastic to protect it all.

The robot has been constructed using Lego™ Mindstorms® Ev3 and it has an Android tablet on it that serves as a rich colorful digital input/output device.

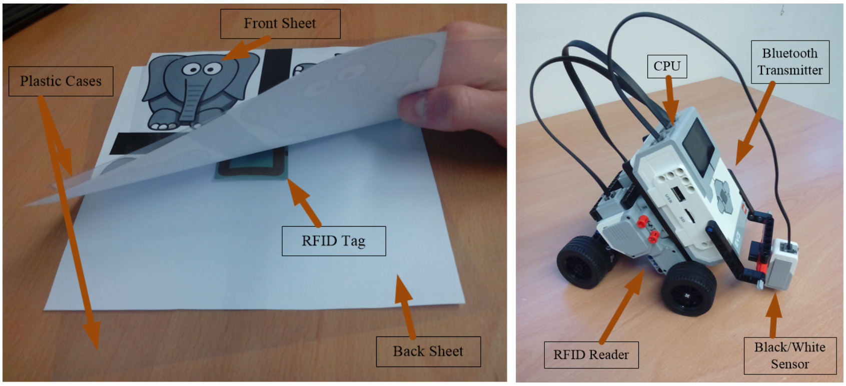

Figure 14.3: Details of the tile (left) and the mobile robot (right).

Figure 14.3 (right) shows the different components this robot is composed of (aside from the tablet). It has a color sensor that differentiates between black and white so it can follow the surface's black paths. Every time it reaches the center of a tile, its RFID reader situated on the bottom reads the tag embedded in the tile and sends its code to the tablet. This one contains the game logic, handles touch interaction, and sends the proper control commands to the robot via Bluetooth.

The system allows several interaction modalities: Users can perform coarse-grained interactions by coupling and decoupling the tiles at will at runtime or by using command cards that are read by the robot's RFID reader. On the other hand, finer-grained interactions can also be achieved via touch contacts on the tablet. Since different tiles have distinct RFID codes, they can provide the game with different information, thereby removing the need of touch input, and leaving the tablet for display purposes only if this would be required. Figure 14.4 shows an example of a touch interaction (left), where the user touches the tablet designing a path for the robot to follow, and of a tangible interaction (right), where the player physically "draws" the path in the surface by rearranging the tiles.

14.4 A Game to Stimulate Cognitive Abilities for the Elderly

Ageing entails a diminution in some physical and cognitive capacities. Examples of these reduced capacities are short-term (working) memory, the ability to filter irrelevant information, divided attention, and visual-spatial attention (Gamberini et al., 2006). This section exemplifies how the prototype described in this paper can be used to help training these capacities and fight their decline through developing cognitive games. An illustrative scenario of a game to improve short-term memory and divided attention is detailed next:

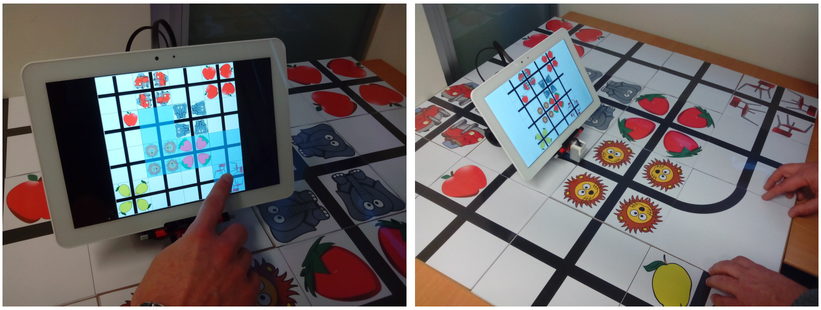

Figure 14.4: Interaction modalities supported. Touch-based (left) and tangible (right).

A therapist arranges several tiles containing pictures on the surface as depicted in Figure 14.4 for the player to memorize. Then, the former turns over the tiles, removing the pictures and leaving only the crossing paths visible. At this moment, the tablet shows a target image and the user must devise a path from the robot position to the location where the displayed figure is. Then, using either touch or tangible interaction, the users draw the trajectory and the robot follows it. The system provides positive or negative feedback depending on the adequacy of the path defined to reach the proposed target. In additional iterations of the game the therapist also includes tiles showing a wrong direction sign to motivate the users to find alternative paths to the target avoiding these tiles.

Following Salthouse and Babcock's suggestions (1991), both the speed of the robot and the rate at which the target elements are displayed should be reduced. According to Rogers (2000), the reduction of the ability to filter irrelevant information affects the selective attention, which depends on the familiarity of the user with the presented objects. Taking this into account, the images to memorize should be easily recognizable by the participants. This game requires using divided attention because players must focus on remembering the location of the images and drawing paths at the same time. This training by itself, as stated by Rogers (2000) enhances divided attention and improves making attention switches. Also, the remembrance of the objects' location and the creation of routes serve as a training of visual-spatial processes.

Another important aim of this platform is avoiding the dangers of social isolation that could provide a similar implementation where each user would hold a tablet. The intrinsic nature of our table-like surface enables collaborative scenarios where several people situate around the physical table and help one another find better pathways and/or simply discuss the game and the situation themselves.

14.5 Conclusions and Future Work

In this paper we presented a prototype of a digitally-augmented tangible surface aimed at constructing cognitive games for the elderly. Not only the table-like design fosters human-to-human socialization via collaboration but also the touch and tangible capabilities bring more natural and intuitive interactions that can appeal ageing users. Hence, the ultimate purpose of the present work is to design useful and usable technology for this special group.

The platform is built with cost-effective materials, and its design allows for a quick setup and a high versatility and scalability. We exemplified the use of the surface with a cognitive game to improve short-term memory and selective, divided, and visual-spatial attention.

As future work, we intend to perform experiments with real users in order to test whether the tangible interaction offers any advantages with respect to digital (touch) both in configuring the layout of the game (i.e., the arrangement of the tiles) and in the problem solving phase (e.g., drawing a path for the robot to follow or giving it specific instructions at run time). Other future experiments will focus on the actual perceived usefulness and usability of the platform and on whether this system has any positive effect on the already enumerated cognitive capacities meant to be stimulated.

Acknowledgments

This work received financial support from Spanish Ministry of Economy and Competitiveness under the National Strategic Program of Research and Project TIN2010-20488, and from Universitat Politècnica de València under Project UPV-FE-2014-24. It is also supported by Conselleria d'Educació, Cultura i Esport (GVA) with fellowships APOSTD/2013/013 and ACIF/2014/214 within the VAL-i+d program.

Part V

Closure

Chapter 15

Discussion

The research hypothesis of this work, as defined in Chapter 1, states that "tangible around-device interactions on multi-tablet environments can be used effectively to build collaborative-learning games for children in primary school, and they present an added value in terms of user experience, performance, and quality of collaboration." To prove this hypothesis, we provide two examples of tangible interactions for these environments that take place around or above the displays, named MarkAirs and Tangibot. In Chapter 1, we elicited seven requirements for these two approaches to fulfill, which revolve around: 1) making use of affordable technology to facilitate their implantation in real educational settings, 2) providing simple scalability mechanisms to allow expanding or contracting the workspace as needed, 3) allowing players' mobility, 4) making the interactions as intuitive and fluid as possible by means of the manipulation of physical objects, 5) enabling the interaction in the space surrounding the digital surfaces that would be empty otherwise, 6) being generic enough to enable different educational games designed by teachers to make use of them, and 7) supporting games in which collaboration is not only encouraged but enforced.

Both MarkAirs and Tangibot are designed to support the previous requirements. Firstly, they rely on tablet devices or smartphones, which are in common use nowadays, and on inexpensive cardboard cards or toys. Only Tangibot uses a Lego Mindstorms robot and some RFID cards, which, even though they increase the platform's cost, can still be afforded by many education centers, especially when compared to other collaborative technologies such as tabletops. The use of handheld devices and affordable tangible materials make the resulting MDE highly scalable, since it can be shrunk or extended easily just by removing or adding (respectively) more tablets and props to it. They also enable the scattering of the interactive elements around big areas, which would allow more players to participate and move around. To cope with the empty space that would be generated in the environment as a result of this dispersion, interaction is conducted by means of the manipulation of physical objects in this space, be it to transport digital information in tangible containers between displays, or to perform gestures/actions that modify the game's state. Both approaches provide generic interaction mechanisms that can be used in different types of games: MarkAirs through the metaphor of "grabbing", manipulating, and "releasing" digital objects, and Tangibot by means of guiding the robot to the proximities of the devices. However, we have designed with them two collaborative learning games that enforce the players' collaboration in order to succeed, either by having to conjointly drive the Tangibot robot or by having to perform MarkAirs' aerial gestures with another partner to solve a problem.

Even though our end goal is to apply the previous interaction techniques in learning contexts, the evaluation of certain learning processes, such as knowledge acquisition, is outside the scope of this thesis. Instead, we have put the focus on the evaluation of the user experience and acceptance as well as collaboration, and designed both interaction mechanisms in a generic way, so that actual educators can provide the specific educational contents for the students to learn.User experience and acceptance is a key factor, because, as has been shown in multiple technological and learning contexts (Bargshady et al., 2015; Pindeh et al., 2016; Tan et al., 2016), the usefulness, ease of use, and fun perceived by children influence their attitude towards the learning application usage and the effectiveness of the learning process.

15.1 On Optical Mid-Air ADIs

An optical mid-air around-device interaction technique relying on the manipulation of a tangible object such as MarkAirs can be used effectively to build collaborative educational games with multi-tablet environments in which physical cards act as containers and manipulators of digital elements on screen, as well as identifiers of players. Also, as shown in Chapter 5, these tangibles can also encode actions which, upon a certain gesture being made with them, can modify game properties without the need for additional on-screen visual widgets.

The preliminary studies with adults described in Chapters 3 and 4 revealed that such an interaction is feasible and usable under a wide spectrum of ergonomic conditions (i.e., being seated or standing, having the tablet placed on the user's dominant or non-dominant side, and having it within or beyond arm's reach). Also, it was shown to present low workload levels, which would enable its posterior use within a serious game, so that the interaction technique would not take too much of the players' attention and concentration. Finally, those studies also proved that it is possible to perform fine-grained gestures above tablets with the technique. Chapters 6 and 7 report on a study that confirmed the previous findings with primary school children, and proved the acceptance, usability, and good precision achievable with the technique by these users.

Those studies led to a multi-tablet collaborative game described in Chapter 7. Children enjoyed building country/monument pairs, not only because of the game topic, but also because of the collaboration aspect (as reported by more than 92% of the participants), which suggests further exploration of this type of game in the future. Teachers also liked the MarkAirs framework in the context of the game, since, as with other technological approaches, it allows for the automation of certain routine tasks such as keeping scores and logging the students' progress. This way, educators can focus on classroom dynamics and helping students, and, after the game, on reviewing each student's performance. During the course of the game, a comparison was conducted between MarkAirs and an analog version of the system in which players built pairs by joining sheets of paper. This was used as a baseline to assess the ease of use and effectiveness of the MarkAirs interaction technique. The results showed that the paper-based version was indeed more effective—roughly, children were able to complete twice as many pairs—and this probably had an impact on the children showing a slightly higher preference for this approach when asked directly. It cannot be concluded though that our interaction technique's performance was bad, since its underperformance was to be expected. It is important to notice that manipulating pieces of paper is trivial for children (they are totally accustomed to it), and the players were first introduced to MarkAirs for the purpose of this study, with no time to train with it first. These resultsmight be due to issues of a technical nature, since many marker tracking losses occurred, which made the children angry. Optical tracking problems were due to abrupt changes in lighting conditions and/or to marker movements being conducted too fast for the device's camera to detect, which happened frequently because of the setting being implanted in an uncontrolled environment ("in the wild") and because of the highly-paced nature of the game. The participants proposed two solutions to make the game more appealing and mitigate this issue: 1) to combine MarkAirs with tactile interactions, and 2) to build a hybrid version which combined tablets and paper. This would suggest that, when used in games requiring the players' mobility or rapid movements, MarkAirs, or a similar mid-air optical technique, could benefit from having the tangible objects act as simple containers of digital elements that, once deposited on screen, could be dragged and rotated with one's fingers.

However, manipulating digital objects on screen via mid-air gestures above the display should not be disregarded. The other studies conducted with MarkAirs to evaluate its precision in manipulation tasks show that users perform left/right, forward/backwards, up/down, and yaw rotation hand movements above the tablets with good precision, with errors less than 5% for all gestures in the termination phase (i.e., at the end of the movement after several corrections have taken place), and less than 12% for all gestures in the execution phase (i.e., during the course of a continuous movement). From the precision study made with adults and reported in Chapter 4 it can be seen that adults have higher precision than children, however the difference is small, mostly when compared to children aged 9 and older. For younger children, interactions should be designed more coarsely, e.g., by requiring a rougher gesture in order to trigger a response in the digital object being manipulated.These slow-paced precision tasks elicited very good impressions from children (with scores of 4.95/5, significantly higher post-test with respect to their initial expectancies). For this, we can argue that performing precise gestures with a technique like MarkAirs would still be interesting, mostly for slow-paced games in which tracking issues are less likely to occur, as explained above.

15.2 On Companion-Based ADIs

Interacting around a multi-tablet environment by manipulating a companion can also enable collaborative learning experiences in children. In this thesis we have showed this through the development of Tangibot, a robot companion the children can collaboratively drive around and interact with the displays by proximity.

An initial version of Tangibot was designed via a participatory design with kindergarten teachers to make it appealing even to the youngest children. The teachers praised its ability to keep the kids engaged for relatively long periods of time, which—as they said—was hard to do because children of these ages lose interest very quickly. They also stated that it was an interesting change of paradigm in their way of presenting knowledge to the kids, as well as a versatile tool to create group activities. Evaluations of the robot were conducted with children aged 2-6 (described in Chapters 8 and 9), revealing the robot as a tool able to maintain kindergarten children in a mental state of flow—i.e., fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity (Nakamura and Csikszentmihalyi, 2008)—which is recognized by different studies as a key factor in promoting learning (Rathunde, 2003; Shernoff et al., 2003). This indicates that the platform had a good acceptance among these children, who stayed amused and focused during the activities. However, it was revealed that more complex tasks such as guiding the robot along a predefined path should be restricted to children older than 3 years old, and, from 5 years old onwards they are able to do it significantly faster, which would enable the use of the robot in a cognitively more demanding activity. An additional finding of these studies was that young children should be in charge only of one movement command of the robot (i.e., have one paddle only) because they make fewer mistakes. This enables distributing the commands between more children, which in turn allows for bigger groups of four.

In light of the previous findings, Tangibot was introduced in a tablet-based MDE and used in a collaborative-learning game for children in primary school based on tangible interactions and physical spaces. Two studies (reported in Chapters 10 and 11) were conducted with children aged 9 and 10 years old to evaluate their experience and collaboration quality using the companion-based interaction technique in a physical space with respect to digital-only versions of the same game. The results indicate that, surprisingly, the participants performed in a similar way in the digital and physical versions in terms of number of questions solved. The one using Tangibot was expected to be less efficient in this respect because using a physical space required the children to move around, which was expected to slow them down. However, the tangible version seemed to present two benefits: On the one hand, the spatially distributed game cells (tablets) on the floor, that required children to move around, enabled the players to exploit task division effectively, so that each player explored a different answer cell and then they discussed which one was correct. On the other hand, the bigger workspace allowed better control of the robot, which improved obstacle avoidance and, in the end, saved more time.

Children found the game in both versions (tactile and tangible) engaging and fun, although no clear differences were found between them. This indicates that even though tangible around-device interactions are novel for children, they are not harder to use and they are as fun as traditional touch-based interactions. With respect to collaboration, its quality was assessed by the metrics defined by Meier et al. (2007). Both interaction approaches were found to support good overall collaboration quality, except in three dimensions: information pooling, sustaining mutual understanding, and time management (this one only in the tangible version). Information pooling was rated by two observers as close to "bad" because the explanations made by the children to one another were not very elaborate and mostly consisted of giving orders (even though they ended up reaching consensus). Similarly, sustaining mutual understanding was rated as close to "very bad" since the participants were not concerned about whether or not the others understood their explanations. These results suggest either a deficiency in the game to support certain aspects of collaboration, which could perhaps be improved by having more open-ended questions to foster further discussion. However, they could also reveal a limitation of the metrics when used with children, since they were initially devised for adults and might mistake childish behaviors for bad collaboration quality. Finally, with respect to time management, this was rated as close to "neutral" but still negatively for the Tangibot-based version. This might be due to the novelty effect of the platform, which made the children spend some time wandering around the physical space. Nevertheless, objectively, as reported above, this poorer time management did not affect the children's performance. The version relying on tangible interactions did outperform the other in some dimensions: reaching consensus, task division, and reciprocal interaction. As for the former, it was observed that the kids discussed and reached a consensus not only to decide what the correct answer was (as happened with the digital version) but also to determine which path to follow by pointing and moving themselves through the board. Task division, as reported above, was more efficient in this version because of parallel exploration. In the tablet-only version, the participants tended to explore the board individually, probably due to the traditional—individual and private—way of interacting with tablet devices. Finally, the reason why reciprocal interaction was perceived as worse in the digital version was probably the fact that it caused more collisions (with the subsequent loss of progress), which entailed all the participants blaming one another.

In short, it was found that the design of the game (its rules and layout) and the tangible interactions supported (with the props and devices), as well as the personal relationships fostered, make Tangibot meet both the conditions identified by the OECD (2013) as necessary to foster collaborative problem solving, i.e., communication, negotiation, and planning; and also the six conditions for successful collaborative learning identified by Szewkis et al. (2011): having a common goal, joint rewards, awareness of all the peers' work, individual accountability of actions, coordination and communication between peers, and positive interdependence. We can therefore conclude that this type of ADI can provide a fun and engaging experience that effectively supports collaboration, exploration, and reflection, which are key to the successful development of playful learning activities (Price et al., 2003). In addition, as described in Chapter 13, we have found that elderly people with no or mild cognitive impairment can also control the robot with fair precision. They also find this interaction enjoyable and capable of triggering positive emotional reactions in them, hence making it interesting to further explore it in collaborative learning contexts to stimulate the cognitive abilities that decline with age or to strengthen bonds with their grandchildren via intergenerational games.

Chapter 16

Conclusions and Future Work

In this work we have proposed two cost-effective approaches to tangible around-device interactions for collaborative-learning multi-tablet game environments: MarkAirs and Tangibot. Whereas the former is an optical solution which relies on no additional hardware besides the tablets, except for several printed cardboard cards, the latter introduces a tangible-mediated companion (in the form of a mobile robot) and other physical props in the environment and is based on RFID technology.

The thesis starts by exploring the literature and making a classification of multi-display environments into a common framework, with the purpose of identifying their dimensions, to serve as a guide for future designers. This taxonomy builds upon previous partial ones and provides a more general and wider conception along three axes: the physical topology of the environment, how the different displays can be coupled together, and the different ways of interacting with the system. Additional considerations are discussed related to the context of the environment, such as who is going to interact with it, where, and what for. We argue for giving as much importance to technical dimensions as to these other considerations, because making the latter drive the design of the former may lead to meaningful technological environments better suited to the users and therefore increasing their chances of success.

We then move on to presenting the interaction techniques designed. After several evaluations, we observed that MarkAirs is usable and undemanding both for adults and for children, and that fine-grained gestures above the tablets can be successfully conducted with it, therefore enabling the construction of more complex games. We also show that, when applied to collaborative games, it can help reduce screen occlusion and interference among the different users' actions, which is a problem that may arise in such settings when only touch interactions are available. Finally, we present a collaborative learning game with MarkAirs and study the experience of primary school children with it.We found that the game is generally well received by students and teachers alike. For the former it is a fun experience, and for the latter it provides a way of keeping track of the children's performance and progress in real time. A comparison was made between the MarkAirs interaction technique and another one relying on the manipulation of pieces of paper. As expected, traditional (paper-based) manipulations outperform our proposal, although the manipulations with MarkAirs are rated between "good" and "really good" on average, and more than 80% of the children expressed their desire to play with it again. In conclusion, this mechanism is revealed as capable of creating collaborative learning experiences and it presents an added value in user experience, although not in performance. Two major design implications are derived from our studies: a) some sort of visual feedback should be used to show the user the state of the recognized marker (either with a small video region on screen showing what is captured by the camera, or as a digital representation of the marker); and b) either lighting conditions should be controlled or interactions should be conducted at a slow pace in order to avoid tracking marker losses.

With respect to Tangibot, we have shown how collaboratively controlling a mobile robot with tangible paddles and achieving certain precision with it is feasible for children from 3 years of age, and even for elderly people with mild cognitive impairment. Furthermore, it provides a fun experience for children and maintains them in a constant state of flow during the activities, which has been identified as promising for learning. The robot was introduced in a multi-tablet setting and complemented with other tangible props, creating an augmented physical playground. A game was created to foster collaborative problem solving among primary school children, and two studies were conducted. One of them compares user experience and acceptance of the game between Tangibot and two other purely-digital approaches: one relying on a digital tabletop and another on a tactile multi-tablet environment. The only significant gameplay differences between the platforms are in the number of wrong answers and the time between answers, which can probably be attributed to the perceived distances due to the board size. Additionally, the observational results of the study provide feedback on specific differences between the three platforms, as well as verifying that the game encourages the use of the skills associated with collaborative problem solving. It provides the first evidence indicating that, despite the current widespread individual tablet-based learning strategies, educational technology for collaborative problem solving skill acquisition should concentrate on collaborative games based on physical spaces in which technology based on having a companion such as a robot is perceived by children as natural and motivating. The other study focuses on the analysis of the quality of the collaboration between the tangible and the tactile multi-tablet platforms. Both versions enable good collaboration overall, with the tangible platform outperforming the tactile one in being able to make the children reach consensus after a discussion, split and parallelize work, and treat each other with more respect. Nevertheless, it was observed that the children manage their time worse with Tangibot, perhaps due to the novelty effect. Design guidelines for such games are provided, consisting of presenting the quizzes to the children at increasing levels of difficulty, and making the questions more open-ended so that they require more elaborate resolution procedures to trigger more conversations.

In short, both MarkAirs and Tangibot have been shown as promising for interaction with multi-tablet environments. However, future studies should be conducted in order to obtain further information about all the capabilities of the techniques to promote collaborative learning. MarkAirs could be enhanced by incorporating marker roll and pitch rotations, which, in conjunction with a tablet-tracking mechanism like WeTab, would enable the cursor to be projected onto other tablets even in an extended-discontinuous logical view of the devices. This, in turn, would extend the interaction space, since one could reach multiple tablets placed beyond arm's length. Additional studies should also be conducted to evaluate the hypothesis that children's performance with MarkAirs increases by extending their exposure to it, and to check if tracking losses decrease by using other types of fiducial markers. Furthermore, as extracted from the participants' requests, other tangible objects should be tested for better acceptance among the children, as well as the combination of mid-air interactions and touch for better performance and user experience.

As for Tangibot, it would be interesting to evaluate the effect of the companion on user experience and collaboration, to see which shapes, degree of intelligence, behaviors, and capabilities (e.g., jumping or moving at different speeds, as suggested by the participants) are better suited for collaborative learning. Similarly, the effectiveness of the direct tangible interaction technique to make the robot move should be studied more deeply alongside direct touch (as in Chapter 14) or other remote control mechanisms. Additionally, since the interaction with Tangibot is usable by and appealing to the elderly, cross-generational games could also be worth exploring to enable, among others, the transfer of knowledge from grandparents to grandchildren, and bond strengthening.

Finally, additional studies should be conducted to determine whether both the interaction techniques presented in this thesis have an impact on other learning variables, such as knowledge acquisition and transfer.

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