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Design, implementation and evaluation of tangible design intefaces for children

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DOCTORAL THESIS

Design, Implementation and Evaluation of Tangible Interfaces for Children

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A Esther, y a mis directoras de tesis: Eva y Sandra;
porque hace falta tener paciencia conmigo.

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Index

1 INTRODUCTION AND OBJECTIVES 17

- 1.1 MOTIVATION 18
- 1.2 OBJECTIVES 20
- 1.3 THESIS STRUCTURE 21

2 STATE OF THE ART 23

- 2.1 TANGIBLE USER INTERFACES 24
  - *2.1.1 Computer Interfaces 24*
  - *2.1.2 Ubiquitous Computing 24*
  - *2.1.3 Tangible bits 27*
  - *2.1.4 Ullmer and Ishii classification of Tangible Bits 28*
  - *2.1.5 Underkoffler classification of Tangible Bits 31*
  - *2.1.6 Fishkin Taxonomy of Tangible User Interfaces 33*
  - *2.1.7 Djajadiningrat Tangible Interaction aproach 38*
  - *2.1.8 Conclusions 41*
- 2.2 TANGIBLE TABLETOPS 42
  - *2.2.1 Active surfaces 42*
  - *2.2.2 Shareable Surfaces 47*
  - *2.2.3 Tangible Tabletops 48*
  - *2.2.4 Conclusions 53*
- 2.3 TANGIBLE TABLETOPS FOR CHILDREN 54
  - *2.3.1 Computer Manipulatives 54*
  - *2.3.2 Digital Manipulatives 56*
  - *2.3.3 Digital Manipulatives on a Tabletop 61*
  - *2.3.4 Children and tangible tabletops 62*
  - *2.3.5 Conclusions 65*
- 2.4 NEW METHODOLOGY FOR MEASURING TANGIBILITY AND NEW CLASSIFICATION OF DIGITAL MANIPULATIVES 66
  - *2.4.1 New methodology for measuring tangibility 66*
  - *2.4.2 New classification of digital manipulatives on a tabletop 67*
  - *2.4.3 Conclusions 70*
- 2.5 CHILDREN CENTERED DESIGN 71
  - *2.5.1 Children Involvement 71*

2.5.2 Evaluating with Children 73
2.5.3 Evaluation Methods for Children 74
2.5.4 Conclusions 81

3 NIKVISION 83

3.1 NIKVision Lifecycle 84
3.2 NIKVision Tabletop 86
3.2.1 Introduction 86
3.2.2 Feasibility 86
3.2.3 Prototype 90
3.2.4 Development 96
3.3 NIKVision Tangible Game 100
3.3.1 Introduction 100
3.3.2 Feasibility 102
3.3.3 Prototype 108
3.3.4 Development 117
3.3.5 Final evaluation 120
3.4 Exploring new games for physical collaborative play 130
3.4.1 Introduction 130
3.4.2 Math game 130
3.4.3 Drum sequencer game 131
3.4.4 Draw game 132
3.4.5 “Asteroids” game 134
3.4.6 “Pirates” game 135
3.4.7 Observed collaborative behaviours 136
3.5 Conclusions 139

4 CONCLUSIONS AND FUTURE WORK 143

4.1 Conclusions 143
4.2 Contributions 145
4.3 Future work 146
4.3.1 Exploring children collaboration supported by digital manipulatives 146
4.3.2 Children with cognitive disabilities 146

ANNEX 1: NIKVISION TABLETOP DESIGN 149

ANNEX 2: REACTIVISION FRAMEWORK 159

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1 Introduction and Objectives

Tangible User Interfaces (TUI) are one of the most recent and promising research fields in Human Computer Interaction (HCI). In recent years, computer devices which offer more natural and intuitive interaction to users are succeeding in the commercial market. Therefore, it is expected that new applications based on the TUI approach will be of interest to consumers. One of the consumer sectors which will benefit most from the rise of TUI applications will be young children. Physical manipulation of toys has been the base of their development and education for many years. TUI can be a perfect approach to bring computer technologies to preschool children. In consequence, this is the moment to research the most adequate methods to successfully apply TUI technologies to the special needs of preschoolers, and this is the framework for the present dissertation.

This first chapter introduces the thesis to the reader. First, the issues which motivated this work are detailed. Then, the specific objectives of this research are listed. Finally, the structure of this document is also explained.

1.1 Motivation

In our modern society, technology has a strong presence in work, spare time and social relations. Moreover, it is present during the whole life of people, starting from the first inclusion of an individual in social life, i.e. nurseries and preschool education (3 to 6 year-old). However, conventional computer stations and interactive applications based on mouse and keyboard are not adequate for young children's cognitive and psychomotor development (Healy, 1998) and do not offer them benefits in fundamental aspects of their development such as group activities, physical playing and manipulative learning (Piaget, 1952). Plowman and Stephen (2005) have described the use of computers in nurseries and the many problems they found in their observations and interviews. There were few examples of teachers' peer support; adults rarely intervened or offered guidance and the most common form of intervention was reactive supervision. In general, teachers are reluctant to use computers in their nurseries, so they are underused and offer, therefore, a limited experience for most children.

Over recent years, multitouch active surfaces are proving an outstanding success. Computer tabletops which become active (the user can interact directly by touching and dragging on the table surface) offer a more intuitive and natural interaction approach, and allow more than one user working together on the same surface. However, there is a risk of missing a great opportunity to bring this new technology to kindergarten children. Mansor et al. (2008) observed young children having problems interacting with multitouch tabletops as these devices require fine muscle coordination, which is usually achieved around the age of seven.

Another promising technology which offers natural Human-Computer Interaction (HCI) are Tangible User Interfaces (TUI). Nowadays, computers are expanding their presence into more and more aspects of our daily life, embedded and even hidden in many conventional tools, furniture, household electrical appliances, clothes… The familiarity and intuitiveness which conventional objects have for people will make technology accessible to all kind of users.

Recent studies about emerging technologies which propose new methods of natural interaction based on physical and manipulative activities, like Tangible User Interfaces (TUI), show potential benefits for children (Zuckerman et al., 2005) (Marshall, at al., 2003) (Hornecker and Buur, 2006). Tangible applications can give them benefits, not only for fun, but also from an educational point of view. Moreover, object manipulation has been taken as beneficial in the development of children since Montessori’s work (Burnett, 1962): “Children build their mental image of the world, through the action and motor responses; and, with physical handling, they become conscious of reality”.

Today, technologies are changing and evolving so quickly that there has been little or no time to build a foundation for the design of games and learning applications which could offer pleasant and useful experiences to children. Research literature is rich in User-Centered-Design (UCD) techniques and methodologies to involve users in the creation of products and applications which are “usable” for people (Norman, 1988). Unfortunately, young children have been kept away from these techniques, as they are rooted in the verbalization of user opinions and thoughts. Only recently have children become of interest as consumers and users of technology, and new research groups have coined the term Children-Centered-Design (CCD), grouping themselves around new specialized forums, meetings and journals. New contributions in practical methods to involve children in the design of new interactive applications for them are one of the most emergent areas of interest in Human-Computer Interaction (HCI) research.

1.2 Objectives

Considering the challenges outlined previously, the main objective of this thesis is to bring computer technologies to preschool educative environments, adapting emerging interactive approaches based on natural and physical interaction to young children. The design of prototypes which use the TUI approach will be made by involving children throughout the process (from concept creation, through prototyping and final validation).

Within this context the work of this thesis focuses on:

- Analising the current state of emerging technologies based on physical and natural interaction (specifically TUI and active surfaces), and Children Centered Design techniques and methodologies to carry out design projects with children's involvement,

- Creating and validating a prototype which supports natural interaction with preschool children, provided by the manipulation of physical objects. This prototype must support exploration of the benefits which this kind of technologies offers to preschool children. All this must be done by following CCD methodologies to involve children in the design and validation of the prototype.

1.3 Thesis Structure

The structure of this dissertation is as follows:

- Chapter 2 presents a state of the art of:
    - The paradigm of Tangible User Interface (TUI) (section 2.1), focusing on the different classifications and taxonomies proposed in the literature to measure the "tangibility" of a TUI.
    - Computer active surfaces (section 2.2), focusing on the techniques used to detect user interaction on the surface, and the emerging proposals to promote collocated work around horizontal active surfaces (tabletops).
    - Computer applications for children based on physical manipulation (section 2.3) focusing on those based on tabletop devices.
    - Techniques and methods to involve children in the design process of interactive products (section 2.5), with special attention to those optimal for the testing and evaluation of TUI.
- Chapter 3 narrates the design lifecycle of NIKVision, which is composed of:
    - A tabletop device to support small groups of children physically playing using toys, and oriented towards use in nurseries and preschool environments (section 3.2)
    - A Farm game designed to explore the benefits of using the tangible interactive approach in preschool children (section 3.3)
    - A set of innovative toys and tabletop games which are designed to reinforce collaboration in children (section 3.4).
- Chapter 4 concludes the dissertation with the main conclusions and the contributions of this thesis. Future areas of research are also outlined.
- Annex 1 gives technical details and blueprints of the final design of the NIKVision tabletop.

- Annex 2 gives details of the new code implementations carried out to adapt the functionalities of the visual framework used in this work (Reactivision) to the requirements of children's interaction on a tabletop.

2 State of the Art

In this chapter, the detailed state of the art used as base of this thesis research is exposed:

Section 2.1 is a state of the art of the Tangible User Interface (TUI) approach. It focuses on the evolution of the classifications and taxonomies applied to TUI applications.

Section 2.2 gives a state of the art of tabletop active surfaces technologies, and the potentials that these devices have to support collocated work and collaboration between users.

Section 2.3 shows the benefits of TUI applied to children education through the analysis of different samples of tangible tabletop applications oriented to children.

Section 2.4 proposes a new methodology to analise, compare and measure tangibility in any TUI application. Using this tool, a new classification of digital manipulatives used as controls in tangible tabletop devices is also proposed.

Finally, section 2.5 gives an overview of the present situation of the Children Centered Design research movement and the different methods especially adapted to involve children in the creation of innovative technologies for them.

2.1 Tangible User Interfaces

2.1.1 Computer Interfaces

A computer-user interface is where interaction between humans and computers occurs. This term includes both hardware and software components. Users need interfaces to send commands to operate the system, and this is provided by the use of input devices. On the other side, computers need to send some feedback to the user to indicate the results of these commands. This is done through Output Devices.

The way digital systems process information (as 1’s and 0’s) has required to design input devices that convert user analogical inputs into digital data suitable for a computer, as well as output devices that convert digital data stored on the computer into analogical outputs that can be perceived by users.

Since the 1970s, Graphic User Interfaces (GUI) have dominated computer users’ everyday lives. Keyboards and mice have been the usual input devices, while monitors and speakers have provided the output.

In order to create some kind of interface which most potential users of technology would be familiar with, the desktop metaphor was created. As computers spread into office environments, they replaced the conventional office desktop — pens, calculator, documents, engagements book, calendar, files - with virtual metaphors: a mice can be used as a hand to drag documents, as a pencil to write text or drawing, as an eraser to delete text or drawings, or to operate a virtual calculator simulating a finger pressing buttons. All interactions produce outputs on a graphic representation of a desktop in a vertical screen in front of the user. This is known as the “Window, Icon, Menu, Pointing device” (WIMP) paradigm. WIMP metaphors must be learnt by the users, who often find them unnatural, which could lead to dissatisfaction with technology.

HCI researchers have been trying to obliterate the WIMP paradigm and desktop metaphor, in order to provide a more natural interaction between users and computers. In the 1980s, early proposals on Virtual Reality interfaces seemed promising within HCI forums. The concept aimed to translate humans into the digital world of computers, so users could interact with a virtual world in the same way that they would in the real one, with no metaphors. Virtual Reality helmets, gauntlets and many other hi-tech but uncomfortable devices were designed as inputs and outputs for Virtual Reality interfaces. It was supposed that advances in input and output devices would lead to the creation of more natural and light virtual reality devices, but few improvements were made through the 1990s. As a result, interaction designers and researchers lost interest in virtual reality, focussing instead on the opposite idea: what about trying to bring computers out of the digital world, into the real analogical one?

2.1.2 Ubiquitous Computing

Mark Weiser, working at the Xerox Palo Alto Research Center (PARC), in 1988, envisioned a future where technology would be miniaturized and globally networked, enabling the distribution of computer devices which could be embedded in everyday objects and environments (Smart Devices):

“[Computer devices] weave themselves into the fabric of everyday life until they are indistinguishable from it” (Weiser, 1991). Inspired by Philip K. Dick’s 1969 sci-fi novel Ubik, he named this paradigm “Ubiquitous Computing.”

The Weiser research team at PARC, created the first application of this vision: “Live Wire” (see Fig 1). Using strings and step motors, system administrators at PARC could perceive network traffic by looking at the movements of strings hanging from the ceiling. This represented the first example of ambient intelligence.

Fig 1: LiveWire installation (Weiser, 1999). Wires hanging of the ceiling move depending of the network traffic of the lab.

Moreover, Weiser created an early classification of smart devices, based on their size:

- Tabs: wearable centimetre sized devices

- Pads: hand held devices

- Active surfaces: interactive display devices

And all should be capable of being input and output system devices.

Wisnesky (1998), from the Massachusetts Institute of Technology (MIT), used this ubiquitous device classification to create the Ambient Room (see
Fig 2), where furniture and walls of a conventional lecture room are active surfaces capable of output and input information. Users manipulate objects (pads and tabs graspable media) to interact with the system (foreground), and they receive feedback from the room ambient (background) (see Fig 3).

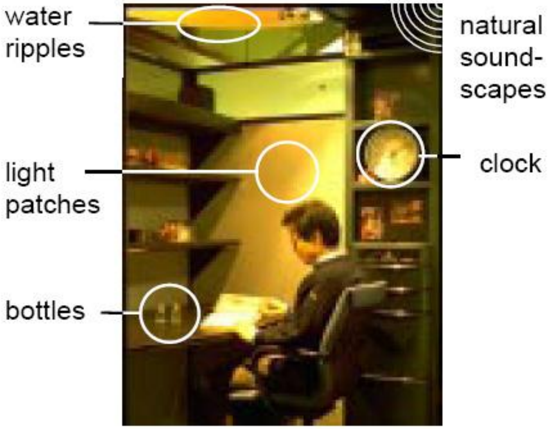


Fig 2: Ambient Room. MIT MediaLab (Wisneski, 1998). The room itself is giving feedback to user through environment changes

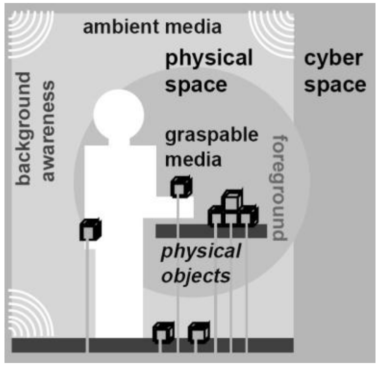


Fig 3: Foreground and background interaction in theAmbient Room. (Wisneski, 1998)

Wisneski took the graspable media concept, from a previous work of Fritzmaurize et al. (1995), also from MIT, who proposed a new paradigm to interact with graphics applications. He exposed that conventional input devices, like the mouse, distributes inputs over time (one input at a time). He suggested the handling of multiple graspable objects (bricks) that are distributed on space as inputs for the graphic application (see Fig 4). The bricks were handled over an horizontal surface that became active using videoprojection. Moving the bricks resulted in moving virtual graphics projected on the table, and physical operations on the bricks, received immediate visual feedback on the same physical place that manipulation occurred.

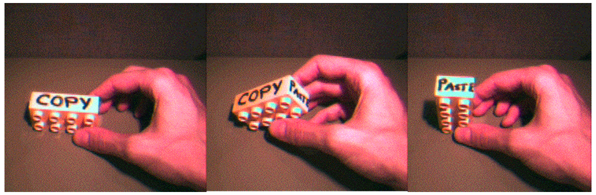


Fig 4: Graspable bricks (Fritzmaurize et al., 1995). User give orders to computer application manipulating and combining graspable blocks.

Both Wineski and Fritzmaurize researchs were directed by Iroshii Ishii. Together with Ullmer, both created the Tangible Media Lab, based on this envision: to represent digital content through tangible objects, which could then be manipulated via physical interaction with these tangibles. The core idea was to quite literally allow users to grasp data with their hands and to unify representation and control. Digital representations were thought to be closely coupled, usually through graphical projections on and around the tangible objects (Ishii and Ullmer, 1997).

2.1.3 Tangible bits

Ishii envisioned a new HCI paradigm after realising that many conventional objects could be interfaces by themselves, providing the user with input and output of information just in the same object. He exemplified this idea with the abacus device. This object makes no distinction between "input" and "output". The beads and rods are manipulative controls of arithmetical operations; and, at the same time, they are physical representations of numerical values.

This is the very essence of the Tangible User Interfaces (TUI): interactive systems in which conventional objects are at the same time, controls and physical representation of the digital information (see Fig 5).

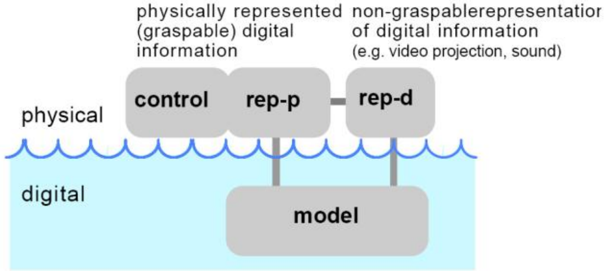


Fig 5: TUI model: Physical objects (up the water line) are used to control the digital model of the application (down water line), and they can also represent (physically or digitally) digital information of the aplication (Ishii and Ullmer, 1997)

This coupled between the physical and the digital world was briefed by Ishii with the Tangible Bits term (joining atoms and bits). Grounded on the Weiser classification for smart devices, he proposed a new one considering how bits and atoms are coupled:

- **Ambient Media**: Any element in the background of the user attention (light, sound, wind, water...) is used as output of digital information. System will use any manipulation and user gesture as input.

- **Coupling of Bits and Atoms**: Seamless coupling of everyday graspable objects (e.g., cards, books, models) with the digital information that pertains to them.

- **Interactive Surfaces**: Transformation of each surface within architectural space (e.g., walls, desktops, ceilings, doors, windows) into an active interface between the physical and virtual worlds.

Ishii was indeed evolving the concept of Ubiquous computing, focusing on making the digital information "graspable" in two ways:

1. Everyday objects are controllers of the digital application

2. Users are aware of the digital information perceiving state changes on the same objects, or through periphery perception using ambient display media (see Fig 6)

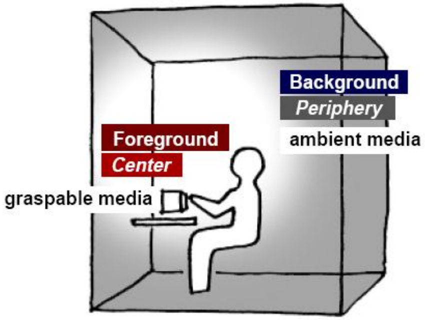


Fig 6: Conventional objects are used as controls and user receives feedback through the room ambient. (Ishii and Ullmer, 1997)

2.1.4 Ullmer and Ishii classification of Tangible Bits

The first application of a Tangible User Interface proposed by the Tangible Media Lab was the MetaDESK: an horizontal active surface in which interaction was carried out using physical models of buildings to interact with graphical maps and architectural data, and a set of physical tools (see Fig 7).

Fig 7: Metadesk application that senses the objects placed on its surface. (Ishii and Ullmer, 1997)

This application was used by Ullmer and Ishii (1997) to model a very early classification of Tangible bits (see Fig 8), based in the analogy of the Metadesk TUI with a conventional Graphic User Interface (GUI). Each graspable object of the Metadesk application was confronted with its counter partner in a GUI:

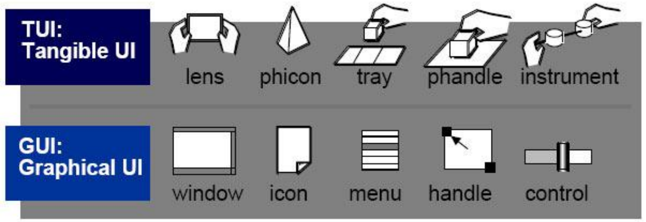


Fig 8: GUI Desktop metaphor(down) vs MetaDESK tangible bits (up). (Ishii and Ullmer, 1997)

- **Lens**: An additional active surface, capable of showing image, aimed to give more detailed graphic information of the image showed on the table surface. The analogy came from the GUI windows, that open and expand information.

- **Phicon**: A new term that comes from the combination of physical and icon. A phicon is an object that has a unique meaning by itself in the application. It came from the icon term in a GUI, as each graphic icon represents an specific kind of file (document, drawing, executable, sound...)

- **Tray**: An object which only function is to select an option from a multiple choice list showed on the active surface. Depending on the position on the surface where this object is placed, an option is triggered. Thus, it is a selector, analogue to the menu selector in a GUI.

- **Phandle**: This term came from combining physical and handle. It is a graspable object than can be moved defining or changing a rectangular area of the active surface, in analogy of GUI handles that enable to resize windows.

- **Instrument**: A very wide concept, that refers to any object that can be manipulated to regulate values in the application (audio volume, colour, size...).

Soon, they realised that this classification was not useful to extend to other tangible applications beyond MetaDESK, as new tangible proposals were emerging (Ullmer and Ishii, 1998), (Ishii and Usllmer, 1999) (Underkoffler et al., 1999). Realising that TUI could be implemented in a great variety of physical methods, Ullmer and Ishii simplified radically the classification of Tangible bits (Ullmer and Ishii, 2000) distinguishing only between:

- **Tokens**: Any physically manipulative element.

- **Reference frame**: Physical spaces in which tokens are manipulated.

This classification was inspired by conventional board games (chess, Monopoly, Backgammon), as Ullmer and Ishii found that are closely related to the TUI interaction model. The rules of a board game set spatial relations between tokens and reference frames. Any piece of a board game (token), gains meaning as it is placed on a particular square of the board (reference frame). Furthermore, a token can play at the same time the function of reference frame, nesting other token (like the Trivial Pursuit wheel in Fig 9).

Fig 9: Hasbro Trivial Pursuit wheel is the reference frame of little plastic pieces.

For example, in the MediaBlocks device (Ullmer and Ishii, 1998) wooden blocks (tokens) are placed and moved along racks (reference frame) on the sides of a conventional computer monitor which displays the digital information associated with the tokens (see Fig 10). Thus, tokens acquire meaning depending on their position on the racks.

Fig 10: Mediablocks (Ullmer and Ishii, 1998). User places wooden blocks around monitor which shows the digital content associated with them.

But again, as new examples of TUI were created, this classification was proved not suitable to describe tangible bits in applications in which interaction does not take place in a limited space, such as TOPOBO or I/O Brush.

TOPOBO (Raffle et al., 2004) was a reconfigurable robotic set of tools, composed of independent pieces that acquire meaning when attached to other pieces (see Fig 11). Users were able to build articulated toys combining the pieces. Once the robot was built, user could move the robot elements (e.g. in a robotic dog, user could move the tail, or the head simulating that the dog was barking barking). Pieces “memorized” the movements, and later they could reproduce the same movement autonomously.

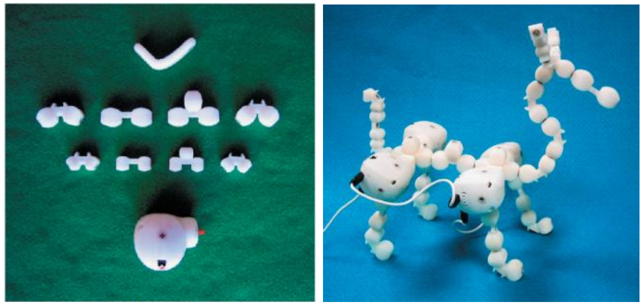


Fig 11: Topobo pieces (left) and sample model (right) (Raffle et al., 2004). Motor pieces are able to memorize user manipulations and later replay them autonomously.

TOPOBO pieces can be seen as tokens in the Ishii classification, but meaning is not coming from any spatial relation within reference frames.

The I/O Brush (Ryokai et al., 2007) consisted on a computer augmented brush capable of painting with the colour or texture of any real object over an active surface (see Fig 12). User was able to touch any object with the brush, and then paint with the captured texture on the active wall. The brush could be classified as a token in the application, and the active wall as a reference frame, but this taxonomy is not able to classify the objects used as ink in the paint application.

Fig 12: I/O Brush (Ryokai et al., 2007). Camera inside the brush captures a picture of any object where the brush is placed. Later, this picture can be used to paint on a computer blackboard.

2.1.5 Underkoffler classification of Tangible Bits

Underkoffler (Underkoffler and Ishii, 1999) proposed a very different taxonomy focusing on the meaning that each tangible bit has in the TUI (metaphor). Different meanings are distributed along a continuous line where each tangible bit could be located (see Fig 13):

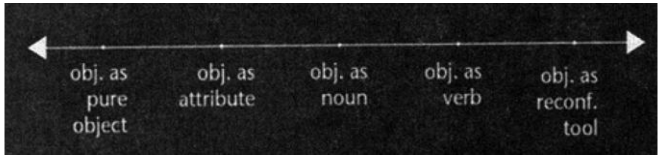


Fig 13: Underkoffler taxonomy of tangible bits (Underkoffler and Ishii, 1999)

- Object as “**noun”**: A “noun” tangible bit acquires meaning with the object itself. It is the equivalent of tokens in the Ishii classification. As an example, in the

Metadesk application, the building miniatures (phycons) are "nouns" (a miniature of the library building represents the virtual library building on the application). Also, in the Mediablock application, each wooden piece represents a digital content, that appears in the same moment a block is placed on the rack.

- Object as "**verb"**: The meaning of a "verb" tangible bit comes from what the object *does.* Without any action, the object has not representation in the system. It serves to the system to *act* on other elements of the application, or on the environment as a whole. In the Metadesk application, lens, phandles, trays and instruments are "verbs", because they are just tools to manipulate the digital content of the application, but they do not represent any content by themselves.

- Object as "**reconfigurable tool"**. In a tangible application, an object is a reconfigurable tool if its meaning depends and changes during its use. For example, in the TOPOBO application, each piece of the set is a reconfigurable tool, as it has different meaning depending on which position takes in the articulated toy, or which movement is memorized on the piece. A reconfigurable tool is how traditionally the mouse pointer is defined in WIMP. A mouse pointer changes its meaning during time (eraser, selector, pen, resize...).

- Object as "**attribute"**: Only an attribute of the object has meaning for the system (eg. its shape, its size, its colour...). Any object can be used in the application as far as it has the "attribute" that the system is capturing. For example, in the I/O bush application any object used as ink to paint with the brush is an "attribute", as the brush only needs the colour or texture of the object.

- Object as "**pure object"**: The only meaning of the tangible bit is that it is an object (as opposite of nothing). It may or may not be important that the object be uniquely identifiable. For example, in the gumball sequencer (Hesse and McDiarmid, 2008), the user can compose beats placing gumballs on holes (see Fig 14). There is not really meaning on the gumballs except for being present on a hole of the table, meaning that it will emit a drum sound. Even though it does not matter if the object is actually a gumball, as far as there is some object in the hole.

Fig 14: Gumball sequencer (Hesse and McDiarmid, 2008). Each ball triggers a music note.

Underkoffler and Ishii (1999) did not pretend to purely classify a tangible bit as only "name", "reconfigurable tools", "verb", "attribute" or "pure object", but locate it in a continuous line from "pure object" to "reconfigurable tool". As each tangible bit has to be placed in a point in the continuous line, this is useful to describe the meaning of any tangible bit used on a TUI, but it cannot describe the whole TUI system, or how tangible a TUI is.

2.1.6 Fishkin Taxonomy of Tangible User Interfaces

Ishii based the definition of TUI in the seamless integration of representation and control of digital data in the physical objects (tangible bits). This gives a simple definition of what a TUI is, but gives little information of how perfect this seamless integration needs to be to consider an application a TUI. Furthermore, concepts to measure the "tangibility" of any TUI and compare different TUI with similar function should be of great interest. Aiming to this, Fishkin (Fishkin, 2004) proposed a taxonomy based on two axis:

- Embodiment
- Metaphor

This taxonomy places a tangible application on a 2D continuous representation to determine the quality of the "tangibility", deduced from how far in both axis it is. Moreover, this representation can be used to determine how any tangible (and not tangible) proposal can be improved to make it more tangible by *pushing* the embodiment and/or the metaphor further in the corresponding axis.

2.1.6.1 Embodiment

From the embodiment point of view, tangible interaction can be decomposed in three stages:

1- Input: user manipulates an object.

2- Process: some kind of computational transformations take place in relation to the physical manipulation.

3- Output: object responds to the user to inform of the result of the manipulation.

Embodiment defines how user perceives these steps tied in the same object. This perception can be set in one of four levels of embodiment (from less to more embodiment): distant, environmental, nearby and full.

1- **Distant**: The user perceives that input and output take place in different objects. This is the conventional embodiment in WIMP interfaces. Mouse is the input object, and monitor is the output object. Distant embodiment is the extreme of the axis with less tangibility. The Doll's Head application (Hinckley et al. 1994) proposes the use of physical doll's head and other props (like small plastic sheets) to visualize on monitor 3D slices of brain images (see Fig 15).

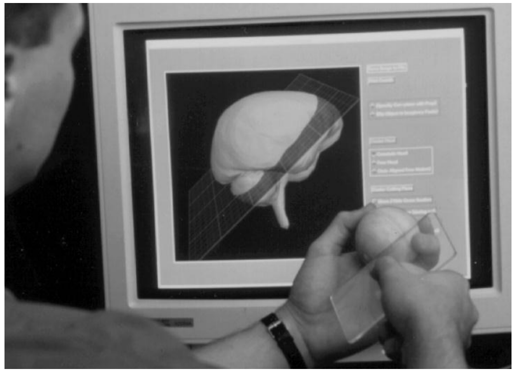


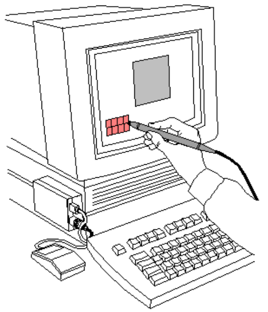
Fig 15: Doll's Head (Hinckley et al., 1994). User manipulates physical tools on a Doll's head to visualize different sections of a 3D virtual head on monitor.

Besides having distant embodiment, this application reflects the TUI paradigm coupling conventional objects with the digital information of the 3D brain images that is being visualized on the monitor.

2- **Environmental**: This kind of embodiment is characteristic of environment interfaces like the ambient room previously described, but they are not limited to rooms or open space applications. The output is not coupled to an object: It is “around” the user. Many audio and music applications like the gumball sequencer previously described have environmental embodiment. The Toon Town application (Singer et al. 1999) is an Internet audio Chat application, in which a user can rearrange physical representations of other users on a board (see Fig 16). The position of each “miniaturized user” determines the 3D location of the voice of the real user using a 3D audio system. So, users can easily recognise the voice of each user in the chat by the relative position of its voice in relation to the physical character on the board.

Fig 16: Toon Town (Singer et al. 1999). Toy cartoon characters are placed on a stand representing different human users of an internet chat.

3- **Nearby**: The input object is different from the output object, but the interaction takes place when they are very close to each other (in contact). First nearby embodied interfaces used light pen devices to control GUI directly by pressing the light pen on the monitor and, thus, getting rid of the distance between mouse (input) and monitor (output) (see Fig 17).



From Computer Desktop Encyclopedia
© 1998 The Computer Language Co. Inc.

Fig 17: Light pen (ComputerDesktopEnciclopedia). First nearby embodiment on a desktop computer.

The I/O brush previously described above uses the same principle as the light pen when the brush paints on an active blackboard. Tabletop devices as the previously described METADESK and Mediablocks have also nearby embodiment between the objects and the table surface.

4- **Full**: Input and output devices are (or are perceived as) the same object. So this is the ideal embodiment on TUI: the object is perfectly coupled with the digital information. The Pcubee application (Stavness et al. 2010) is a very representative example of full embodiment (see Fig 18). User interacts with a digital 3D scenery that seems to be inside a cube. The virtual scenery responds to user manipulations of the cube as it is not virtual and user perceives the digital world totally coupled with the physical one.

Fig 18: Pcubee (Stavness et al. 2010). User manipulates virtual objects shaking the cube toy.

The TOPOBO robotic application is also full embodied, as user manipulates and perceives feedback in the same object, but this time the output is not image. Input is made by users moving the plastic pieces of the robot, and output is made by the same pieces, autonomously imitating the movements previously made by the user.

2.1.6.2 Metaphor

Metaphors have a great importance in HCI. Conventional WIMP applications have been designed using the desktop metaphor (Malone, 1983). Graphics showed on the monitor are a metaphor of a conventional office desktop: files, folders, documents, text sheets... Interactions in WIMP are metaphors of real world manipulations: deleting a file is made by dragging the file icon to a graphic trash; the calculator application is graphically similar to a physical calculator... and the mouse is a variable metaphor: in the calculator application the mouse pointer represents the user finger; in a word processor, sometimes represents a pen, and sometimes represents an eraser. In a paint program when drawing, the mouse pointer represents a brush. The quality of a metaphor roots on how easily the user can perceive the analogy between computer interface actions and real-world similar actions.

When using conventional objects in TUI applications, metaphors can be more natural to user’s mental models: would the user understand that the mice pointer is a brush in a WIMP based paint program?... and on the other side, in the I/O brush application, would user understand that the physical brush tool has to be used as a brush in the tangible paint application? TUI makes better use of user cognitive models, with better HCI metaphors.

In order to quantify the metaphor in TUI applications, Fishkin has rescued the old Underkoffler classification, noticing that "noun", "verb" and "attributes" of the tangibles bits are in fact describing the metaphor of the objects in the system. However, Fishkin did not use the linear representation. He claimed that "noun", "verb" and "attribute" are independent metaphors and that the more types of metaphors are present in a system, the more tangible the system is (see Fig 19).

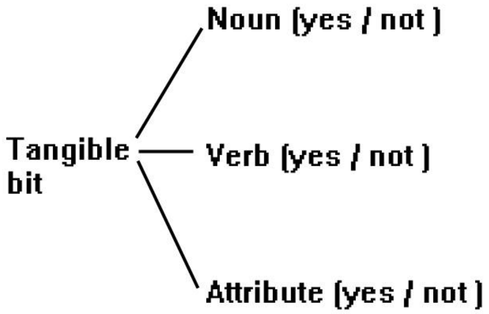


Fig 19: Fishkin metaphor taxonomy. (Fishkin, 2004)

In consequence, the metaphor of any TUI application can be analised by answering yes/not in relation with a "noun", "verb" or "attribute" metaphor present/absent in the system:

The TOPOBO application uses small plastic pieces with no metaphor by themselves. They are only motorized pieces with no meaning in the system, either their shape, their colour or how they are manipulated.

Mediablocks application has "noun" metaphor: Each wooden block represents by itself an image of video digital content. The presence of a block, triggers the digital content on the monitor. Toon Town, as well, has "noun" metaphor, as each Toon character toy represents a user on the chat.

The Gumball sequencer uses only "verb" metaphor. It does not matter the object: the same ball placed on different hole, triggers different sound; and it does not matter the colour or shape, even a plastic box can make the same function, and its different attributes has not meaning on the system. Pcube application also uses only "verb". The only object is the cube, which is also the system. So the only meaning of the system is the actions made with the cube (shake, reorient, hit ...)

Metadesk application combines "noun" and "verb". The plastic miniature buildings (phycons) represent the real building on the digital map. The rest of the objects (lens, phandlers, trays and instruments) need to be manipulated to act on the system, so they are "verb" metaphors.

Doll's head has also "noun" and "verb" metaphor. Each object (doll's head, and plastic sheet) are represented on screen. When the two kinds of objects are combined and plastic sheets manipulated over the head, they trigger the different visualizations of the brain (manipulating the digital content).

Other TUI examples use only "attribute" metaphor. The Mark Burton's WaterBoard application (Waterboard web ref.) can be used with virtually any object. The users can paint on the wall, place objects, or even touch the wall, as the system retrieves the shape of the objects placed on the wall to simulate water flowing (see Fig 20).

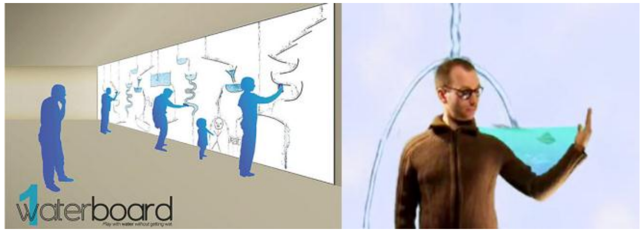


Fig 20: Waterboard. (Waterboard web ref.)

The full metaphor measure is achieved when the system uses "noun", "verb", and "attribute" metaphors. The I/O Brush application combines all metaphors. The brush ("name" metaphor) is used to capture the colour or texture ("attribute" metaphor) of any conventional object, and then, the brush acts ("verb" metaphor) by painting on the active wall.

Another example is the Sandscape application (Ishii et al., 2004). It consists on a box filled with sand. User can model the sand with the hands to create landscapes. The system can texture the landscape through video projection, simulating wind currents, or the effects of water floods (see Fig 21). The sand has not meaning by itself; only its height ("attribute") is used by the system. The manipulations of the user while modelling the sand ("verb"), creates the virtual landscape. User can place wooden pieces to represent ("noun") buildings on the landscape, and see how wind or water affects them.

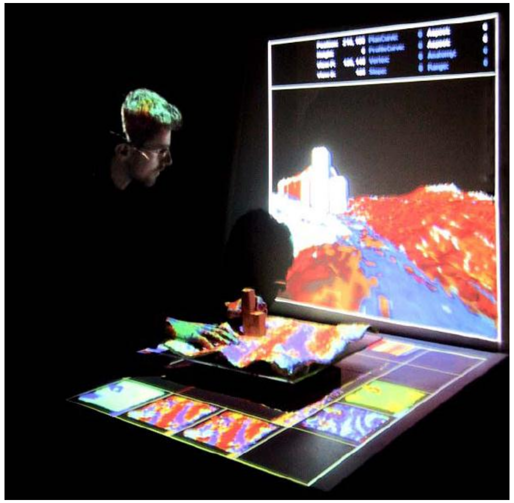


Fig 21: Sandscape. (Ishii et al., 2004)

The Fishkin taxonomy for metaphors is based on previous classifications of tangible bits. So, it is useful to quantify the metaphor of the physical artefacts used on a TUI, but it may have problems to describe the interaction with the system; i.e. what happens when two different TUI applications use the same tangible bits, with the same meaning, but with different interaction approach? Here it is an example of two different interactive proposals in which the Fishkin taxonomy for metaphors is not able to quantify two different tangible approaches:

In the 80's, a controlled electronic car became very popular among children. Its movements were programmed via a keyboard on top. Children were able to input by the keyboard a sequence of movements (straight 1 meter, turn 90º left, straight 2 meters, ...) and then the car executed the sequence autonomously (see Fig 22).

Fig 22: M.B. Big Trak.

Using the Fishkin taxonomy, this toy has "nearby" embodiment since input takes place using a keyboard attached to the car and the output is the car itself, and has only "verb" metaphor since manipulations of users have the meaning of the actions that car reproduces later.

With the same functionality, Sketch-a-move (Sketch-a-move web) proposed the same concept of programmable car toy, but the difference is that the user programs the movements by drawing the path directly on the top of the car using a pen (see Fig 23)

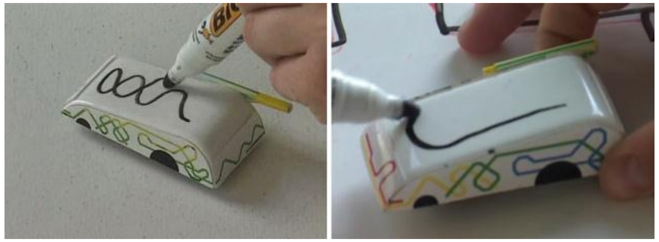


Fig 23: Sketch-a-move (Sketch-a-move web ref.)

As both systems use the same physical tangible bit (a car with sensors on its top), the Fishkin taxonomy gives the same quantity for embodiment ("nearby") and metaphor (only "verb") in both systems. However, there is no doubt that these proposals are very different from the tangible point of view. The difference relies in the interaction: The Sketch-a-move proposal has a more natural interaction that the classical toy, as orders are introduced to the system in a more direct and intuitive way. The taxonomy proposed by Fishkin is not able to measure the metaphor of the interaction with the system. It is focused on the meaning of the tangible bits, but forgets the interaction component

2.1.7 Djajadiningrat Tangible Interaction aproach

Until this point, TUI research was mainly carried out in the computer science area. But recently, other disciplines (arts, architecture, philosophy, and especially product/industrial design) are having a voice in the TUI research. The emerging digital technologies have been of interest of many product designers that have been creating devices coupled with digital content from even before Ishii coined the Tangible bits term. In 1995, industrial designer Durrell Bishop proposed a Marble Answering Machine (Poynor, 1995), in which voice messages were digitally embedded into marbles and could be later played by placing the marbles into a mould on the machine (see Fig 24). This design was already reflecting the approach later exposed by Ishii as the essence of TUI. Marbles were both physical representations and controls of the digital information (incoming voice messages).

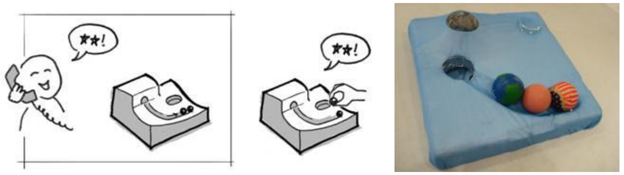


Fig 24: Marble answering machine. (Poynor, 1995)

The Marble answering Machine can be classified using the taxonomies presented until this moment:

- In the Ishii's classification marbles are the tokens of the system, and the holes, where marbles emerge or are placed in to listen messages, are the reference frames.
- In the Underkoffler's classification, the marbles are "pure objects", as there is not distinction between one marble or another or even other similar object as gumballs.
- Using the Fishkin's taxonomy, the system has "environmental" embodiment, as the output is given through ambient audio; and only has "verb" metaphor, as the meaning is only given by manipulating the marbles on the machine.

However, Horneker and Buur (2006) claimed that these classical classifications of TUI are data-centred (coupling of digital data and conventional objects, objects as controls and representations of digital data...) and they are not considering TUI relation with social, cultural and historical aspects, as any other product designed to be used by people. Product design might give a new perspective to analyse TUI as a product designed to enable **interaction** between people and the digital world. This is the reason that, recently, TUI research community is distinguishing between two terms:

- **Tangible User Interfaces (TUI)**, that refers to questions related to computer technology and HCI.
- **Tangible Interaction (TI)**, that refers to design approaches of products based on the digital-physical coupling. Designers have to focus on designing complex behaviour that is digitally controlled and has no inherent relationship to product form (Djajadiningrat et al. 2004).

Djajadiningrat et al. (2004) have analised the relationship between materiality and cultural meaning, while they were looking for the cause that so many mass-consumer electronic devices feels "computeresque", with a computer-like interaction style (menus, decision-trees). They realised that most of this devices are designed to communicate clearly which action was required (press a button, slide a slider...), but it is not important what kind of action is suggested with the appearance of the device or what the result of the action would be. Considering this unbalance, Djajadiningrat distinguished two approaches on designing interactive products: the semantic approach and the direct approach (see Fig 25):

Fig 25: Semantic approach (left) vs. Direct approach (right). (Djajadiningrat et al., 2004)

- **Semantic approach**: This approach is characterised by reliance on **metaphor**, in which the functionality of the product is compared to an existing concept or product with which the user is familiar (‟this product is like a...,” ‟this functionality resembles...”). The appearance of the product and its controls become signs, communicating their meaning through reference. Products resulting from this approach—either hardware or software—often use control panels labelled with icons. Controls communicate actions through previous experiences of user and the meaning of each control is communicated through icons. The appearance of the interface is only for inviting to an arbitrary action which then triggers a function.

- **Direct approach**: This approach takes behaviour and action as its starting point. Here, the basic idea is that meaning is created in the interaction. Affordances only have relevance in relation to what users can perceive and what users can do with their body. Users see both appearance and action as carriers of meaning. The same way, people are used to deduce many information from material properties using their senses: rust and dust give an idea of time without use, size gives an idea of weight. The direct approach uses the richness of user sensory system and physical world (textures, material, weight, sound...) to give meaning to the application. Thus, metaphor is not rooted in user previous experiences or knowledge (this should be used this way, because this looks like ...), but in the way user perceives an object, and the meaning of his/her actions in the object (described by Djajadiningrat with the term **feedforward**).

Recovering the Big Trak toy example exposed in section 2.1.6.2, it can clearly be deduced that this toy has been designed using the semantic approach. It was designed during the big popularization of electronics and home computers. Thus, its interface is based on controls used in most of electronic devices at the time (buttons), individualized by icons to give meaning to each one (see Fig 26). But many buttons were iconized with symbols that have no meaning without previous experience on computers (e.g. CLR for clear action). This toy is oriented to whom? Children or parents who work with computers?

Fig 26: M.B. Big Trak keyboard interface of Big Trak are iconized with symbols or abbreviations.

Comparing it now with the Sketch-a-move toy (see Fig 23) it can be seen that this is a direct approach of the same design. The path of the car (action) is directly connected with the path drawn by the user on the car (affordance). Materials (car white surface and black marker) are perceived by the user (feedforward) as carried of meaning (painting a path in the car with the marker triggers the action of the car repeating this path).

It can be seen that the process followed to design the interaction with a tangible system have an influence on the “tangibility” of the interaction. Consequently, classical classifications of TUI need to be combined with the more actual design approaches that are coming from the TI research.

2.1.8 Conclusions

This chapter has briefly described the short history of TUI, from the first proposals and classifications, that focus on the interface (TUI), to the new proposals coming from product designers that focus on the interaction (TI).

After analysing the origins of TUI applications, and how new examples have forced researchers to evolve and create new taxonomies to include them, it can be concluded that analysis and classification of any system that couples conventional objects and digital data must consider the direct design decision taken to carried out that coupling.

2.2 Tangible Tabletops

2.2.1 Active surfaces

Surfaces have a strong presence in our life: floors, ceilings, walls, tables, windows, blackboards… They play many roles in society: vertical blackboards have been used in education from centuries; also socialization and communication have so much to do with horizontal tables during all human history. In these days, where technology is having an important role on people education, communication and socialization, technology and surfaces have combined to create a new concept: Active Surfaces. In previous section 2.1.2, Active Surfaces are pointed as one of the smart objects recognized by Weiser in his Ubiquitous computing envision. He claimed floors, walls, tables, as a way to show digital information in user environment. Computer augmented surfaces were supported for the first time by Pierre Wellmer in the Digitaldesk application (Wellmer, 1993). Wellmer used the ubiquitous computer envision of hiding technology to the user, to remove computer stations from office table desktop and return it to its original pre-computer state, but augmenting it with image projection and computer visual recognition of user manipulations on the table (see Fig 27).

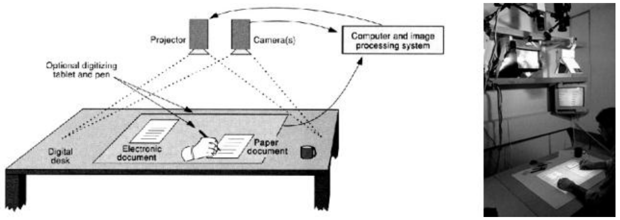


Fig 27: Wellmer Digitaldesk sketch and prototype (Wellmer, 1993).

Also Ishii recognized active surfaces as one of the methods to couple physical and digital worlds. His first creation, the Metadesk (Ullmer and Ishii, 1997), was in fact an interactive surface on which the user interacts using a set of objects and physical tools to navigate through a digital map projected on the table. It is easy to see that active surfaces' embodiment always is "nearby" (see section 2.1.6): user puts in contact his/her body, fingers, or other objects with the surface to control the system, and receives output on the surface close to that contact point.

Active surfaces can be oriented vertical, horizontal, or even tilted. Orientation has strong influence on the function of these devices (Kruger, 2004). Horizontal surfaces are well suited for socialization and collaborative applications. Computer augmented surfaces which are horizontal or nearly horizontal are named "Tabletops".

There are as many kinds of tabletop implementations as different kinds of conventional tables. Also, there are as many ways of interact with a tabletop application, as uses has a table. Nowadays user's fingers has become the most popular way of interacting with digital information on a tabletop.

2.2.1.1 Multitouch Interaction

Multitouch is the ability for which a digital system allows interactions determined by the simultaneous contact of multiple fingers on the device where the graphical user interface is displayed. First applications of multitouch appeared at the beginning of the eighties (Metha, 1982) (Lee et al. 1985). They were based on a frosted glass in which user pressed with the fingers on one side. On the other side, a camera captured the glass area. Using visual recognition algorithms, the fingertips on the glass could be tracked as light blobs (see Fig 28)

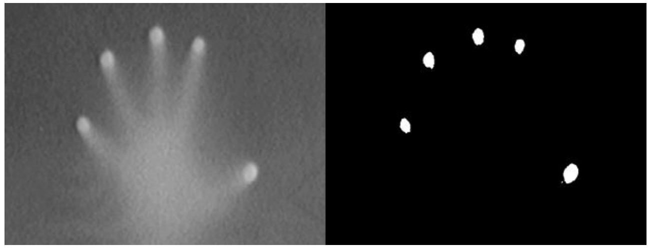


Fig 28: Multitouch interaction: (left) Camera captures fingers over a frosted glass, and (right) software thresholding to track finger blobs (Schöning et al., 2009).

The robustness of finger detection and tracking relies on the algorithms that deal with the image captured by the camera. However, this task can be optimized if the illumination below the glass is designed to contrast the light on the fingers from the rest of the glass. Earlier proposals of multitouch surfaces used the Diffuse Illumination (DI) technique: light comes from below the glass illuminating the fingers (see Fig 29). This technique is easy to implement, but the problem relies on that the rest of the hand receives some light, too; therefore, the camera does not capture a totally clear image of the fingers, but it is contaminated with the rest of the hand. In consequence, tracking of the fingers becomes difficult and unreliable.

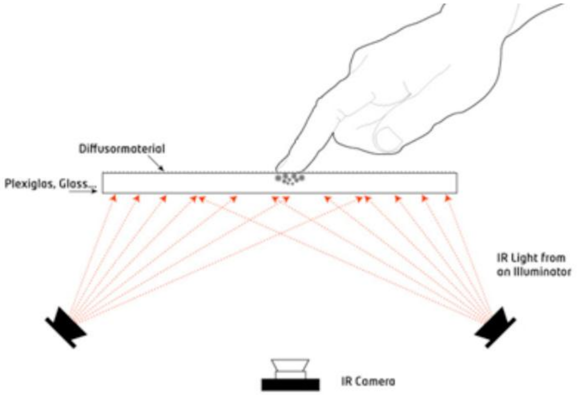


Fig 29: Diffuse illumination technique for multitouch interaction (Schöning et al., 2009)

The alternative to DI is known as Frustrated Total Internal Refraction (FTIR) (Han, 2005) and substitutes the frosted glass by a compliant acrylic surface that is edge-lit by arrays of LEDs all around the surface. That way, the light is "trapped" reflecting inside the surface. In the spots where fingers press the surface, light is blocked illuminating clearly the fingertip (see

Fig 30). In consequence, no light can reach the hand, which is not in contact with the surface (see Fig 31).

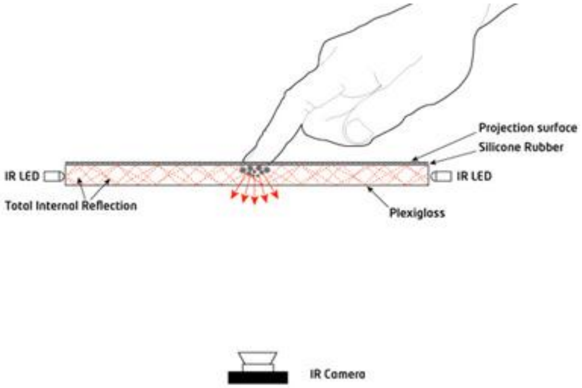


Fig 30: Frustrated Total Internal Refraction technique for multitouch interaction (Schöning et al., 2009).

Fig 31: Camera capture of hand using FTIR (Schöning et al., 2009).

In both techniques, surface is usually illuminated using close Infrared Light (IR), which travels in a frequency close to the red colour, but below the visible spectrum of light. There are two reasons to work with IR on multitouch surfaces:

- Active image on the surface can be showed using an LCD screen or through projection. In both cases, all light is in the visible spectrum. Using IR light to illuminate the fingers does not interfered with the visible light of the screen or projection.

- Camera image can be disturbed by ambient light conditions. Using IR illumination, camera has an IR filter, so it is not able to see visible light on environment. Most of lamps only emits visible light or have little IR emission, so the camera is not interfered by the room illumination.

Multitouch tabletops are one of the most emergent technologies for consumers. Many technology companies have started recently to sell devices based on this technology: Microsoft Surface, DiamonTouch, Reactable, SmartSurface, Philips Entertable, TouchTable and many others.

In the non-commercial area, a growing community of Do-It-Yourself (DIY) designers has emerged thanks the many open-source and GPL license software to track fingers on surfaces. Most of them have adopted the “FrameWork” approach, which enables to develop multitouch applications with independence of the visual recognition software (see Fig 32). The Framework runs as an independent program that retrieves and analyses the image from the camera, identifies finger blobs, and even recognises the gestures that the user is making with the fingers (drag, rotate, scale...). Those data are packed and sent to the program in charge of the multitouch application, which outputs image on the surface in relation to the user's fingers interactions. That way, designers of multitouch applications can use any tool and platform to develop their applications as far as they also implement a client to receive the network packets sent by the framework program. Popular Frameworks for multitouch are Bespoke (Bespoke web ref.), Reactivision (Reactivision web ref.), CCV (CCV web ref.), Touché (Touché web ref.) and Touchlib (Touchlib web ref.).

Multitouch researchers and designers are now placing their efforts in making suitable taxonomies of the actions that the user can trigger on a tabletop, and the natural gestures associated with them (Wobbrock et al, 2009). The user manipulates digital content projected on the surface using finger gestures on the surface which are simulations (or physical metaphors) of similar manipulations on a physical table with physical objects: e.g., users drag documents and pictures on a multitouch application with the same gesture as they drag papers and photos on a table. Grounded on that, many gestures have been designed using direct metaphors (see Fig 33 up), but many other are being designed using semantic metaphors and have not direct equivalence in physical world (see Fig 33 down).

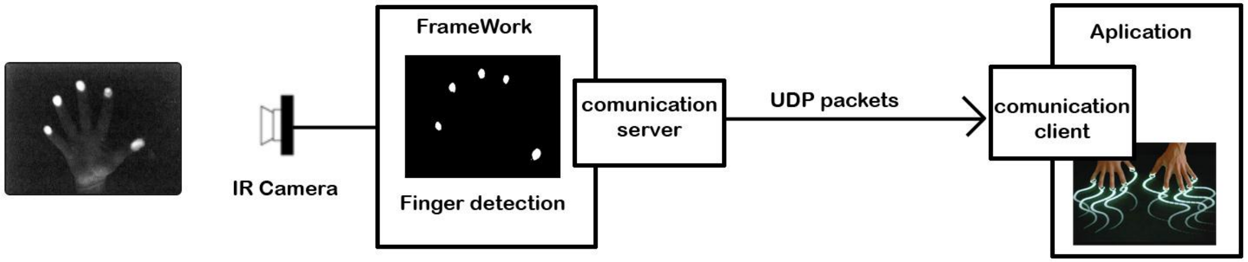


Fig 32: Framework approach for multitouch development.

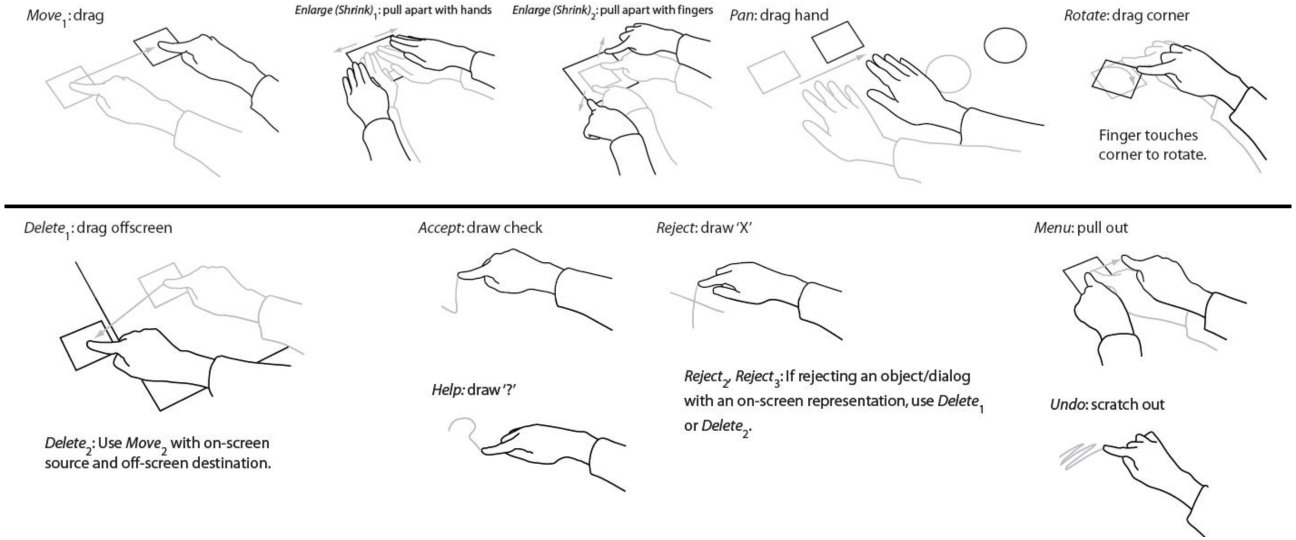


Fig 33: Different gestures on a tabletop surface. Above: based on direct metaphors. Below: based on semantic metaphors (Wobbrock et al., 2009)

New GUI operating systems, like Microsoft Windows 7 (Hofmeester and Wixon, 2010), incorporate multitouch capabilities, recognising the potential of multitouch interaction to replace traditional mouse devices. Therefore, they are reusing WIMP interfaces in which mouse can be replaced by pointing with the fingers on the GUI. However, traditional GUI controls based on WIMP interaction (buttons, handlers, frames, menus...) suitable for mouse devices must be revised to the particular characteristics of multitouch interaction (Jiang et al., 2008) because of:

1. Interactive objects can be totally occluded by the fingers.

2. Pixel precision mouse pointer is now replaced by imprecise finger area.

3. Multiple users may be touching the same controller at the same time, "stealing" each other the control, and might avoid completing the operation.

The first two points should be easily overridden with the redesign of conventional WIMP controls (scale or relocation of control components). However, the 3rd point is bringing out a more fundamental problem: while multitouch interaction enables more than one user interacting at the same time, reusing traditional WIMP based controls and graphic interfaces would lead multitouch applications to single-user interaction (Sun et al., 2006). At this point, designers are proposing new concepts for active surfaces that are far away from "old" WIMP concepts, in order to bring together multiple users working around a tabletop.

2.2.2 Shareable Surfaces

Conventional table furniture has been usually associated to social interaction and collaboration: sharing food during dinners, sharing documents during meetings, and even ludic activities become social when they take place on a table: board games, card games...

Until now, the domination of WIMP based applications in computers has impeded the development of computer-supported cooperative work, except from remote collaboration (that place with users working in different and distant computer stations). Collocated collaboration in WIMP based applications has led to asymmetries concerning the access and creation of information (Rogers and Rodden, 2004). One person may often dominate the interactions by monopolizing the keyboard, mouse, or pen. Once a person is established in a particular role (for example note-taker, mouse controller) he/she tends to remain in it. Moreover, those not in control of the input device, might found difficulties to get their suggestions and ideas listened.

As far as multitouch proposals are influenced by WIMP based control models, trying to adapt single user applications into multi-user collaborative applications will lead to sequential interaction and rigid and inflexible collaborative experiences (Begole et al., 1999). Maybe it is time to look for better inspiration sources for controls that promote better sharing and equal access to digital information on the same surface.

Rogers and Rodden (2004) have observed the different roles of users around a multitouch surface. They noticed that social interaction (sharing ideas, take a turn, respond, confirm, or participate) tended to happen at the same time that interaction with the tabletop. Many tabletop implementations (Jordá et al., 2007) have taken unconventional design decisions to strength symmetry between users and tabletop surface building a circular tabletop and designing a GUI with radial symmetry (see Fig 34) to promote equal collaboration and eliminating head position, leading voices, or privileged points of view and control.

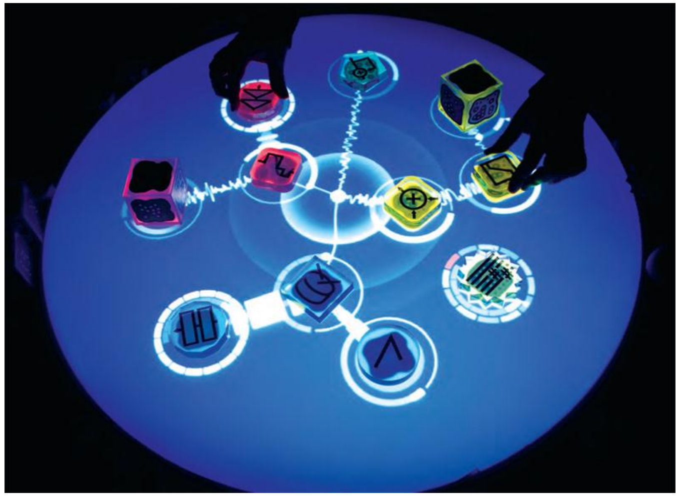


Fig 34: Reactable radial interface (Jordá et al. 2007).

2.2.3 Tangible Tabletops

Another possibility of tabletop devices is to support interaction by the manipulation of physical objects on their surface. One example is the MetaDesk application exposed on chapter 2.1.3 which has a set of objects that the user can place and move on the surface to navigate and extract information from a digital map.

Tabletop interaction possibilities broaden with the inclusion of objects as controllers far beyond the gestured-based multitouch interaction:

- User can drag objects on the surface (see Fig 35 left) and the system tracks the position and speed of any object on the surface.

- User can turn objects (see Fig 35 center). Depending on the tracking technique used on the table, the system is able to track the orientation of the object.

- Multiple object interactions (see Fig 35 right). There is no limit on the number of objects that can be placed and moved over the desktop (as long as there is free space on the table). Thus, objects can interact, establishing relations between them.

Fig 35: Interaction with objects on a tabletop. Left: drag, center: turn, right: multiple object interactions

The Reactable tabletop (Jordà et al. 2007) uses this interaction approach to create a collaborative application to create music (see Fig 34). Users place plastic discs on the surface around the center of the table surface. By turning the discs, user changes sound properties associated with that object (speed, pitch…). Reactable defines two meanings for the disc objects:

- Sounds: When placed on the table, the sound associated with that object plays. These objects are "noun" metaphors (see section 2.1.6): their physical presence is represented in the virtual world by a sound or melody.

- Filters: When a filter disc is placed near a sound object, a virtual connection appears on the surface and the "filter" modifies the "sound". Filter parameters are changed by turning the disc. These are "verb" metaphors. Their only presence has not meaning by themselves, but in relation with "sound" objects.

As exposed in this sample, using objects on a tabletop interactive surface fulfils the seminal ideal of tangible interaction of adding digital information to everyday physical objects, and coupling control and physical representation of digital content in physical objects. For that reason this kind of tabletops are called "tangible tabletops".

Considering the "tangibility" of this kind of tabletop, the interaction possibilities can be broadened when the intrinsic affordances of conventional objects are used (i.e. using a direct approach design cited on section 2.4.1). For example, an eyedropper is a conventional object with a very clear affordance: the rubber ball can be squashed or released to slurp and spit liquids (see Fig 36). Zigelbaum et al. (2008) has proposed the use of an electronically modified eyedropper to "physically" resolve the "cut&paste" WIMP concept in active surfaces. User can slurp digital content into de eyedropper, and later split them on the surface by placing the eyedropper over the digital content showed on the surface (see Fig 37). Material properties of the eyedropper are also used to give feedback to the user: light and haptic feedback on the rubber ball are used when some digital content is "trapped" inside the eyedropper.

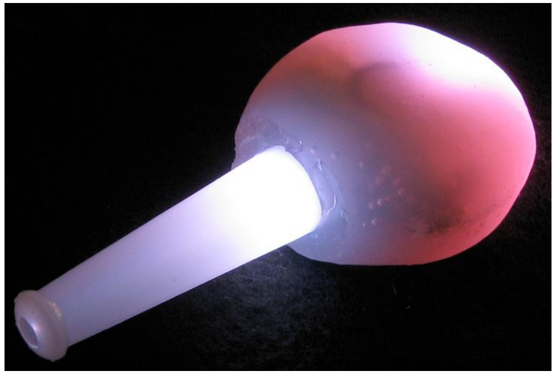


Fig 36: Tangible eyedropper (Zigelbaum et al., 2008)

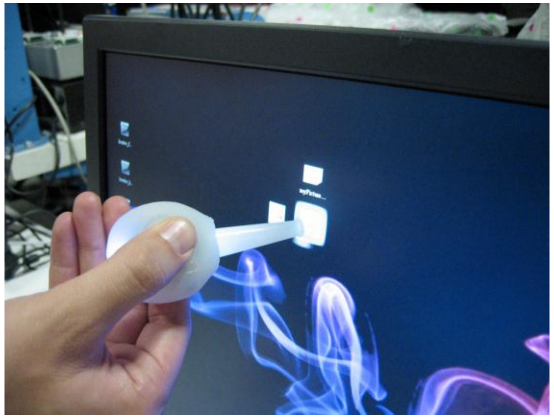


Fig 37: Cut&paste with the eyedropper on an active surface. (Zigelbaum et al., 2008).

This tangible eyedropper concept illustrates how TUI can improve classical operations of GUI interfaces with direct embodiment and metaphors, granting, at the same time, multiple user interaction with the application (as far as each user has an eyedropper).

Technically, enhancing a tabletop device to be able to track objects manipulated on the surface brings challenges different from tracking fingers in multitouch devices. While fingers do not require individualization (all detected fingers are considered by the system equally), different objects need to be identified by the system and tracked individually. Thus, objects need some kind of “digital identification” to be retrieved by the system. The most popular method to digitally identify objects is based on the use of passive Radio Frequency Identifications (RFID). A RFID tag is a small circuit that can be remotely activated by a reader that emits radio waves. RFID tags usually contain a small silicon chip and an antenna. The waves emitted by the reader are sent back by the RFID tag with its identification embedded. The reader can sense presence and identity the tag near it. RFID tags are small (like a stamp or even smaller), which allows “tagging” arbitrary sized objects by attaching a RFID tags to them (see Fig 38).

Fig 38: RFID reader and RFID tag in a keyholder (Phidgets).

The RFID reader only identifies presence when a RFID tag is a few inches near the reader, and returns its ID to the system. Therefore, this technique does not track position. To overcome this limitation, some tabletop are based on using arrays of readers as Audiopad (Patten et al., 2002) (see Fig 39) and PROBONO (Göttel, 2007) (see Fig 40).

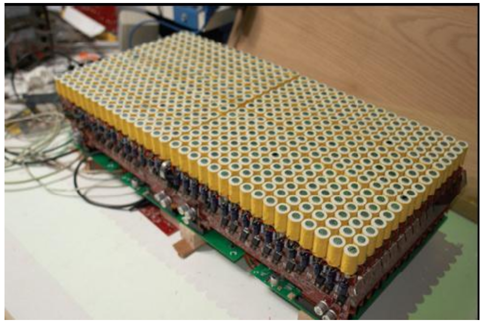


Fig 39: Audiopad (patten et al., 2002) structure of RFID array readers.

Fig 40: PROBONO (Göttlel, 2007) tabletop tracking a RFID augmented toy.

RFID identification of objects on a tabletop device is robust, but, while identifing an object with a single RFID tag is cheap, building and array of readers under the table surface is complex and expensive.

The D-touch tabletop (Costanza et al., 2003) proposes an alternative for object tracking based on visually identifing the objects. A printed pattern is attached to objects in order to help the system to visually recognise them through a digital camera. Based on the well-known algoritms used to recognise printed bar codes, Costanza et al. (2003) designed a set especial printed markers (called fiducials) (see Fig 41) and optimized image recognition algorithms which translate the fiducial to a digital identification on the interactive application. Also, image algorithms track the position of multiple fiducials placed on the tabletop surface (see Fig 42).

Fig 41: D-Touch fiducials printed on wooden blocks (Costanza et al., 2003).

Fig 42: D-Touch tabletop with camera over the surface (Costanza et al., 2003).

As this approach is based on image recognition of the image captured by a camera that sees the whole table surface, multitouch interaction can be combined with object manipulation as far as IR illumination is optimally designed to reflect on finger tips and on printed markers. As described in section 2.2.1, Diffuse Ilumination (DI) technique is suitable for illuminating fiducials placed on the surface, but finger tracking is not enough reliable. On the other hand, Frustrated Total Internal refraction (FTIR) technique is optimized for finger-tip illumination, but printed markers do not receive enough IR light to be recognised. The solution raise from a combination of both techniques, provided by a special acrylic surface that enables frustrated internal refraction of IR light, but at the same time diffusing some amount of light out of the surface (see Fig 43). This technique is known as Diffused Surface Illumination (DSI).

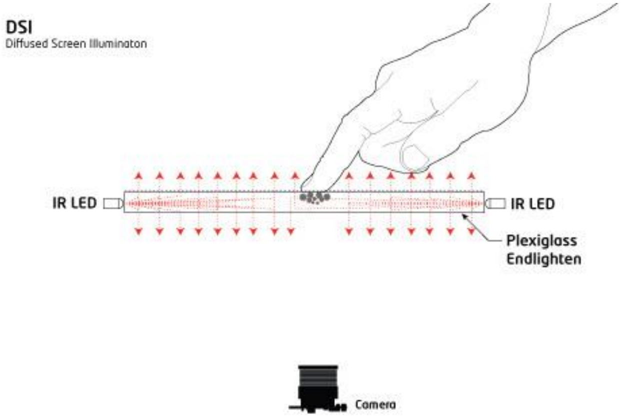


Fig 43: Diffuse Surface Illumination technique for multitouch and fiducial recognition. (Schöning et al., 2009)

The Reactable tabletop (Jordà et al., 2007) is the evolution of the D-Touch tabletop, enabling finger and fiducial tracking using DSI (see. Fig 44) and improving the design of fiducials markers. Kaltenbrunner and Bencina (2007) implemented the Reactivision framework to visually recognize finger and fiducials analysing the image captured by a camera connected to the system. The information retrieved by the Reactivision software is packed using the TUIO standard (Kaltenbrunner et al., 2005) and transmitted using UDP packets to the software in charge of the interactive application and the image output on the table. Furthermore, the D-Touch fiducials were redesigned by Reactivision to enable also orientation tracking of objects with a new set of "amoebas" fiducials (see Fig 45).

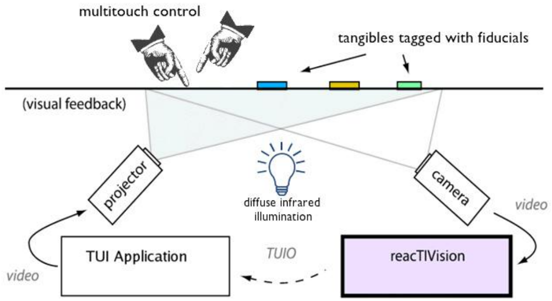


Fig 44: Reactable configuration (Jordà et al., 2007).

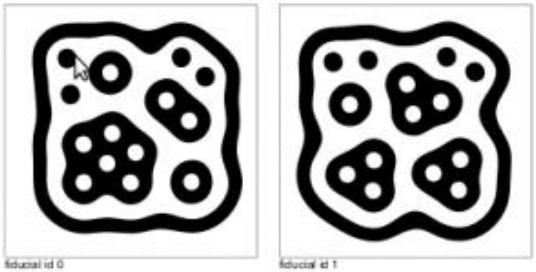


Fig 45: Reactivision amoebas (Kaltenbrunner and Bencina, 2007)

The design of the Reactivision software using the framework approach and its distribution as freeware software has enabled a growing community of tangible tabletop developers to easily prototype, build and develop innovative proposals of tangible tabletop applications.

2.2.4 Conclusions

Interactive tabletop devices bring the benefits of face-to-face interaction and collaborative work to computer applications. But this will only take place if interface and interaction are optimally designed to enable and promote multiple user interaction. Many recent multitouch applications for tabletops are designed reusing old WIMP concepts and controls, which lead to classical computer non-collaborative work. Innovative TUI interaction approaches should bring direct metaphors to interaction on tabletop surfaces, allowing natural interaction and equal collaboration around tabletops.

The present thesis proposes the use of a tangible tabletop device to bring group playing to kindergarten children. Tangible interaction will be provided by augmenting conventional toys with Reactivision fiducials, enabling the system to detect movements and rotations of multiple toys on the table surface.

2.3 Tangible Tabletops for Children

2.3.1 Computer Manipulatives

Nowadays, computers, laptops and, more recently, interactive whiteboards are becoming familiar devices in school environments. However, a study of preschool and kindergarten classrooms indicated low use of digital technologies by most teachers (Cuban, 2001), as it is traditionally believed that young children must reach the operational stage of concrete operations before they are ready to work with computers (Gelman and Baillargeon, 1983).

Non-computer educative activities for preoperational children are oriented to develop their symbolic function using manipulation and handling to help them to build their mental image of the world (Piaget, 1952). The pedagogical values of object manipulation were promoted by Montessori (1949). Children can better solve problems handling materials than they can with only pictures. Children investigate the properties and behaviour of manipulatives; acting and establishing relationships with the physical elements, exploring and identifying them, recognizing what effects they produce, detecting similarities and differences, and then comparing and quantifying. This way, they go from manipulation to representation.

Recent studies comparing the influence of using manipulatives with not using them in education (Raphael and Wahlstrom, 1989) (Sowell, 1989) discovered a paradigmatic situation: it cannot be assumed that pedagogical concepts can be ‘read off’ from manipulatives. That is, pedagogical activities based on manipulatives do not guarantee that the educative concept is transmitted to the children (Clements, 1999). Although kinesthetic experience can enhance perception and thinking, understanding does not travel through the fingertips and up the arm (Ball, 1992). In this context, computers have an increasing potential in early childhood settings. Computers bring the benefits of transmitting concepts by combining visual displays, animated graphics and speech; the ability to provide immediate feedback; the opportunity to explore a situation; and individualization.

Most computer educative applications oriented to young children use WIMP based interfaces to provide virtual representations that are just as personally meaningful to students as physical objects. Many math applications use virtual representations of concrete objects to arrange basic additions and subtractions mouse-dragging this “computer manipulatives” on a virtual environment (see Fig 46). Also, puzzle computer games represent basic geometric shapes that can be manipulated (moved, rotated, flipped, …) with the mouse the same way as physical ones (see Fig 47).

Fig 46: "Double- Trouble" Math educative application (Clements, 2002). Children drag with the mouse virtual representations of cookies to the cake to give the correct numerical answer.

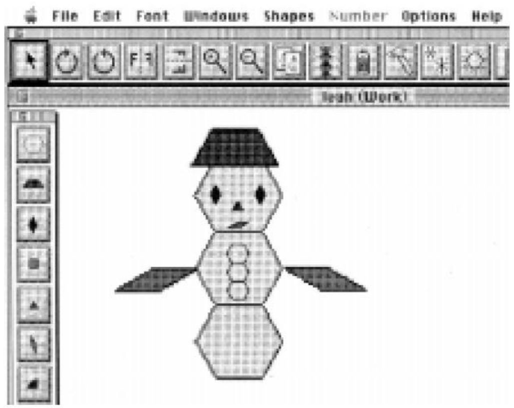


Fig 47: "Shapes" (Clements, 2002). Children manipulate virtual shapes with the mouse to build more complex shapes.

Sarama et al. (1996) assessed how "computer manipulatives" can provide unique advantages by:

- offering a flexible and manageable manipulative, for example, one that might 'snap' into position.
- providing an extensible manipulative, for example one that can be resized or cut.
- linking the concrete and the symbolic with feedback, such as showing concrete blocks dynamically linked to numeric symbols.
- recording and replaying students' actions.
- providing personalized help and adapting activities to child progress.

Using computer applications, children receive numerous opportunities to practice, explore and learn through trial and error, receiving immediate feedback of their progress.

On the other hand WIMP based computer educative applications do not offer physical activities and social interactions to young children. They must split their attention between the 2D/3D virtual environments on the computer screen and the keyboard and mouse they are using to control the application. Furthermore, these input devices limit multiple children interaction. In nurseries and preschools environments, computers are usually used by only one child, while the others play with physical activities, or, if used by small groups, children take roles, with one child controlling the game, while the others participate by voice and pointing at the monitor, or just observing. Due to the importance of physical and group playing in this development period, many educators consider inappropriate the use of computers in young children education.

2.3.2 Digital Manipulatives

From the dawn of the humankind, children have been playing with physical objects, in a physical space, and interacting physically each other. For that reason, computer games have not catch on with fathers and educators as an option for young children entertainment: children need to move, play with other children, and play with physical toys to develop their imagination. In spite of that, computer games are gaining a dominating position of entertainment for children. As described by Mallone (1981), videogames attract children with impossible and imaginative virtual worlds created with impressive graphics and sound (fantasy), propose multiple and progressive goals to complete (challenge), and provoke children's desire of discover new environments and challenges as they progress in the game (curiosity). Educative computer applications also take advantage of the strong motivation that videogames offer to children, combining it with the capabilities of digital technologies to transmit pedagogical content, as described in the previous section.

In present days, children are confronted in a dispute of two ways of playing: traditional physical games, and computer videogames. Many designers are proposing TUI as a solution in which traditional playing mixes with digital entertainment, through the use of conventional toys to control and represent digital gaming. That way, designer takes advantage of children's deep familiarity (and deep passion) with toys. At the same time, Resnick et al. (1998) pioneered on this research by developing a new generation of "digital manipulatives" (computationally enhanced versions of traditional children's toys). By endowing these toys with computational and communications capabilities, they were able to transmit a new set of pedagogical contents for children to think about (in particular, "systems concepts" such as feedback and emergence) that have previously been considered "too advanced" for children to learn. Resnick digital manipulatives were implemented using LEGO programmable bricks (Resnick, et al., 1996) which enable to connect a wide variety of sensors, LEDs, speakers… in order to create a "smart device" (see Fig 48). Bricks are small enough to be embedded in conventional toys. For example, Resnick created the BitBall, a rubber toy ball, with a programme brick inside. Children can program behaviours to the ball using a desktop computer, and transmit the new behaviours to the ball. That way, ball emits sound and changes light colour depending on the way children move them, or communicates with near Bitballs…

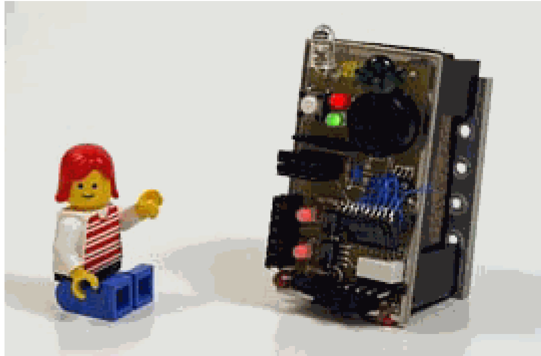


Fig 48: Lego programmable brick (Resnick et al. 1996)

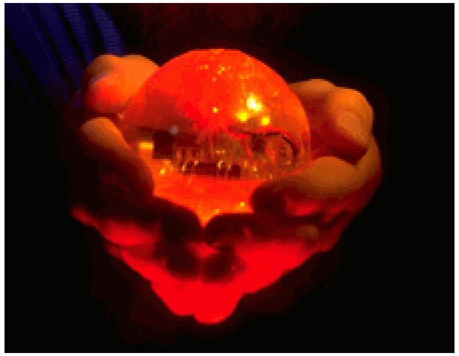


Fig 49: Bitball (Resnick et al. 1998)

The Resnick's envision evolved to a more sophisticated set of computer augmented Toys: Zowie Smart Toys (Shwe, 1999). Zowie playsets consisted of a physical toy with movable pieces that are connected to a conventional desktop computer. A CD-ROM videogame was included with the toy. Using Zowie Smart Toys, children were able to play the videogame without using the mouse and keyboard, but moving the articulable pieces of the toy (see Fig 50). Zowie games offered several modes of play (Discovery and Exploration Play, Hands-On, Active Play, Problem-Solving Play), each fostering different aspects of the children's development.

Fig 50: Zowie Ellie's Enchanted Garden (Shwe, 1999)

Fotijn and Mendels (2005) proposed a similar approach of computer augmented toy, without feedback on a computer monitor. StoryToy was a computer augmented stuffed farm toy with touch sensors and RFID technology. In StoryToy feedback was achieved only with audio (see Fig 51). Furthermore, audio was also an input to the system. Children could create their own stories playing with the farm and speaking to the toy. Their voices were recorded by the toy, and later other children were able to reproduce the story recorded before. In contrast with Zowie Smart toys, Fontijn avoid any "computeresque" element visible on the story toy, claiming that traditional toys have very clear physical affordances that children naturally use to start playing with them with little or no instruction.

Fig 51: StoyToy, farm game augmented with sensors and voice recording (Fotijn and Mendels, 2005).

Zuckerman et al. (2005) claimed the potential of Digital manipulatives to transmit pedagogical contents that involve change and dynamic behaviour over time. While Physical manipulatives introduce preschoolers in abstract concepts such as quantity, numbers, geometric relations, which are static; digital manipulatives can be used to model temporal and dynamic processes (for example, the BitBall can be programmed with especial behaviours related to the velocity or acceleration of the ball).

Traditionally, in preschool education, two kind of physical manipulatives are used with children: **Froebel** (1826) and **Montessori** manipulatives (1949). Zuckerman et al. suggested that digital manipulatives in TUI can also be classified as Froebel or Montessori (digital) manipulatives, expanding their pedagogical values:

- **Froebel digital manipulative** are building blocks that enable children to design real world things, objects or scenarios that can be computer augmented. For example, with the ActiveCube (Watanabe, 2005) children can connect cubes to build new structures, as a horse (see Fig 52), that have a virtual representation on computer screen. Children can move and turn the physical structure to control the virtual one and interact with the virtual scenery.

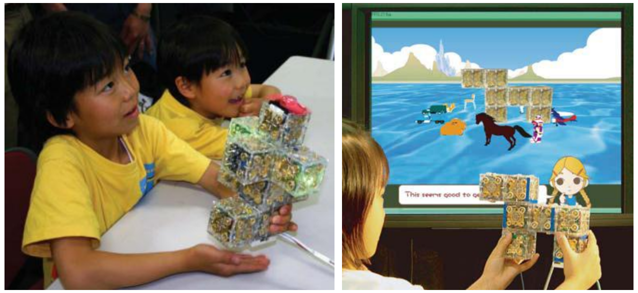


Fig 52: Active Cube aplication (Watanabe, 2005)

- **Montessori digital manipulatives** are primarily focussed on modelling conceptual and abstract structures. For example, Rogers et al. (2002) created Chromatorium. It is a TUI oriented to preschool children that teaches how colours mix to produce new colours. Children manipulate cubes with different colours on each face. When they close the faces of different cubes, they can see on screen how these colour produce a different one (see Fig 53).

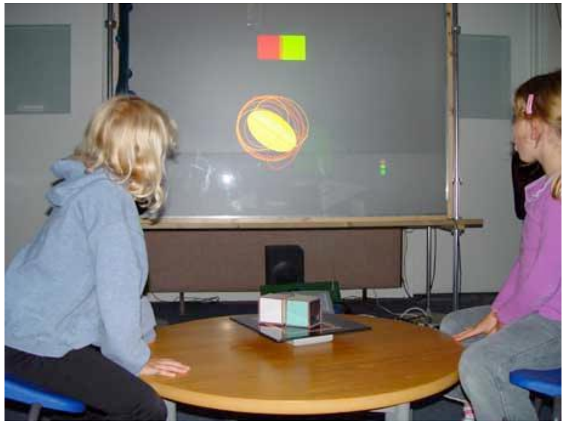


Fig 53: Chromatorium application (Rogers et al., 2002)

The physical affordance of a digital manipulative inherently determines its meaning or function. Froebel digital manipulatives represent or build real world structures, so there is a semantic mapping between the manipulative and children knowledge. Hinske and Lampe (2007) noticed that many toys resemble objects used in the adult world (e.g., tools such as a hammer, a car, or an entire household) and children imitate their usage by what they have been taught or perceived themselves. To research the influence of the metaphors of toys, they built an Augmented Knight Castle (Hinske and Lampe, 2008) (see Fig 54) and observed how children perceived the semantic meaning of each toy. The physical appearance of toys empowered the children to easily understand the role or function of them, and therefore allowed fast and intuitive usage. In addition to that, children could focus on what he/she wanted to do instead of how, since this mapping is totally independent of the underlying technologies. Using the semantic mapping, Hinske and Lampe observed how children created relationships between groups of toys (e.g., the dragon toys are the enemies of the King's Knights, resulting in injured toys during combats, and later healed by closing potion toys to the injured toys; sword toys are used to combat dragon enemies) (see Fig 55). Again, this mapping was mainly based on the physical appearance and the rather obvious roles of the toys in the play. However, they observed that semantic mapping very much depends on education, age and, even more importantly, on the cultural background: in other countries with different cultures or political or religious situations, such a mapping might not be feasible.

Fig 54: Augmeted Knight Castle (Hinske and Lampe, 2008)

Fig 55: Toy semantic meaning defines relationships between different toys (Hinske and Lampe, 2007)

On the other hand, Montessori manipulatives have abstract appearance, and have no semantic mapping with other real world structures that children may know. Marshall et al. (2007) suggested that this manipulatives get the meaning from the **readiness-to-hand** notion. This refers that when using the manipulative, user treats it as almost as if it were invisible (as its appearance has not meaning); and instead user focuses on the task manipulative is used for. In contrast, the **presence-at-hand** refers to Froebel digital manipulatives in which meaning is perceived by children from their appearing and extracted from their knowledge of the object that the manipulative resembles.

For example, the exposed TUI Chromatorium application focuses on the "readiness-to-hand" notion. Children focus on the way the application works, and from that, learning emerges (nearing two colours produces a new one on screen, the learning of primary and secondary colours follows). Interaction in TUIs based on "readiness-to hand" digital manipulative is mainly **exploratory***,* as children use the manipulatives to explore the virtual world of the application and learning its rules (in the Chromatorium, children discover the rules of colour mixing by getting close the colour faces of the cubes).

On the other side, applications like the Augmented Knight Castle focuses on the "presence-at-hand" notion. Children using this kind of applications are "imaging" an external representation of their own activity (a medieval battle between knights and dragons). Interaction in TUIs based on "presence-at-hand" manipulatives is mainly **expressive**, as children use the manipulatives to express they imagined histories. Learning from expressive application can emerge by embodying some theoretical description of the world on it. The Augmented Knight Castle was used to show children medieval poems and describe the society of that historical period.

Marshall et al. also suggested that productive learning results from a cycle between the expressive and exploratory interaction approaches. In the expressive approach, the TUI system can embody some theoretical description of the world, and in the exploratory approach, learner might reason the mechanisms by which the TUI works. An example of educative TUI that uses both expressive and exploratory approaches is the Illuminating Light (Underkoffler and Ishii, 1998). The system comprised a large table on which digital manipulatives representing lasers, lenses, and mirrors could be manipulated. The system virtually represented the behaviour of light passing or reflecting through these objects (see Fig 56)

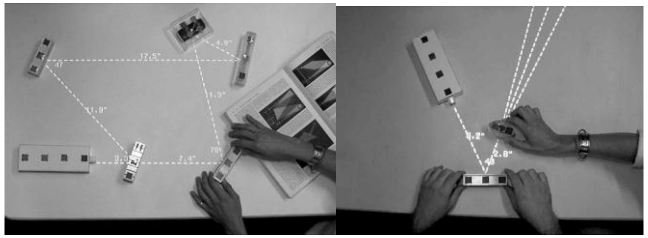


Fig 56: Iluminating Light TUI (Underkoffler and Ishii, 1998)

The system provided the learners with "presence-at-hand" manipulatives. They need to perceive them as representations of real laser emitters, mirror, or lenses and build a structure combining them. But the interaction is explorative (not expressive), as the system simulated a model of optics to explore and where no kind of history of interaction is constructed.

2.3.3 Digital Manipulatives on a Tabletop

In conventional gameboards (e.g. chess, go, backgammon…) physical game pieces are used to visualize the state of the game and the interaction of the players with it. Users interact with the pieces always in relation to the board surface by moving, placing, stacking or rotating them to achieve the desired action. Thus, physical appearance of the pieces has no meaning of how to use them, but have the meaning of what is the function of each piece in the game logic. For example: in the chess game, the board is divided into a regular grid. That way, players perceive that chess pieces are moved from one board square to another independently of the pieces appearance. Moreover, chess pieces have different functions (move and attack other pieces using different rules). The physical appearance of the pieces is perceived by the players as the function of the piece on the game (king, queen, pawn…).

The analogy with board games was considered by Heijboer and van den Hoven (2008) in the design of tangible tabletop games for children. They created 'Totti', a tabletop game about American Indian culture oriented to ten year children (see Fig 57).

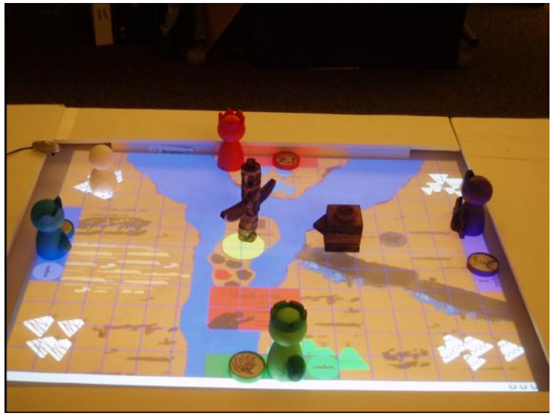


Fig 57: 'Totti' tangible tabletop game (Heijboer and van den Hoven 2008)

When designing the digital manipulatives of the Totti game, they distinguished between two kinds of objects:

- "Carrier" artefacts (manipulatives that resemble the god and its power, see Fig 58). These are related to the "name" metaphor exposed in section 2.1.6, as the presence of these artefacts are linked with a virtual element of the game (a god of water, fire…).

- "Functional" artefacts (manipulatives that only resemble the power of the god e.g. water, fire… see Fig 58). These are related to the "verb" metaphor exposed in section

2.1.6, as their presence only affects or modifies attributes or parameters of the game.

Fig 58: Digital manipulatives of the 'Totti' tabletop game (Heijboer and van den Hove, 2008). Carrier artefacts represent gods in two different levels of abstraction (up). Functional artefacts represent god powers in two different levels of abstraction (down).

In a comparative study of different designs of manipulatives with a group of 10 year-old children, Heijboer and van den Hove found important differences between designing carrier and functional artefacts. Carrier artefacts can be designed with high levels of iconicity, i.e. artefacts have a clear visual link with the things they represent in the game and are realistic looking. Nevertheless, symbolic artefacts have a less clear link with the game element they represent; they include more abstract elements and need to be learned by the players through experience.

2.3.4 Children and tangible tabletops

As seen in the previous sections, educational games can be effectively implemented with both computer manipulatives (WIMP applications) and digital manipulatives (TUI applications). Fails et al. (2005) carried out a research to compare the same educative application implemented as a conventional computer game and as a tangible tabletop game (see Fig 59) oriented to preschool children. They found important advantages in the tabletop implementation. Children showed more interest, engagement in the physical environment, and also they qualitatively learned more in the tabletop environment than in the computer environment.

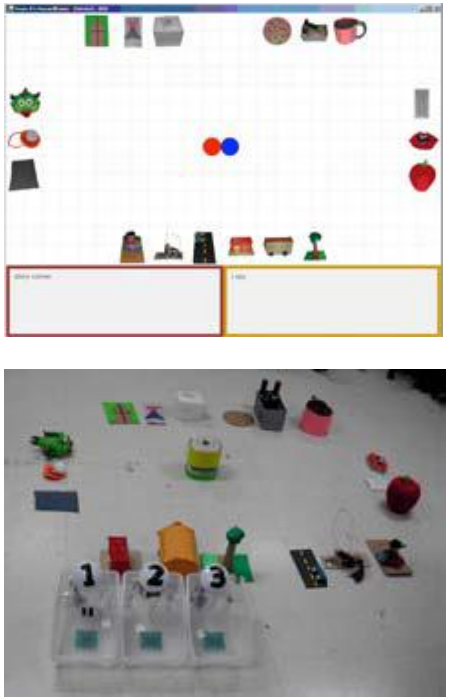


Fig 59: Above: Conventional WIMP game. Below: The same game implemented as a tangible tabletop. (Fails et al., 2005).

A similar study was later conducted by Xie et al. (2008) comparing a conventional physical jigsaw puzzle game, a WIMP computer version of the same puzzle, and the same in a tangible computer augmented tabletop. Many children had problems to complete the puzzle in the WIMP version, as they had difficulties on performing pieces rotations using the mouse. This was not a problem in the conventional and TUI versions as it was performed in the natural way. Children played the three versions of the game in pairs. Collaboration strategies were very different comparing the WIMP version with the two physically based puzzles. Despite the single mouse on the WIMP puzzle, most children found a way to collaborate with each other, by taking sequential turns during their play or one child pointing at the screen or giving verbal suggestions to the partner. In the conventional and TUI versions, pairs solved the puzzles using parallel, independent play in which they seemed to be absorbed in their own activity but they still observed each other's actions and expressions and often copied them. Also, in some cases, their verbalizations revealed a conscious strategy to work cooperatively by dividing puzzles areas between them. When interviewed, all children report the same enjoyment in all three versions; however, significantly more pairs in the physical versions repeated the puzzle a second time.

The advantage of the physical based implementations relies on that augmented tabletop games do not set a relation between the player and the virtual game alone, but also add the richness of the social situation to the virtual domain. Players are confronted around the table facing each other in intimate distance. A dense social situation is stimulated by close face-to-face interaction that integrates discussion, laughter, and all kinds of nonverbal communication hints that are integral elements of conventional tabletop games. For this reason, interactive tabletop technology have increasing potentials in preschool environments because it combines the physical and face-to-face interaction style of traditional small-group children playing with the enhancements of computer technology (Morris et al., 2005).

First applications of tangible tabletop for children were designed for educational purposes, and assessed that young children were able to use and understand computer augmented tabletops, creating new collaborative learning experiences. For example, TICLE (Scarlatos, 2002) was developed for children that are "turned off by math and science" (see Fig 60). Describing the development, Scarlatos states that the tangible interface should "use computers to enhance a physical collaborative learning environment, rather than dominate it" and "respond to student actions (or inaction) as it attempts to guide students without giving them answers".

Fig 60: TICLE tangible tabletop (Scarlatos, 2002).

READ-IT (Sluis et al. 2004) is a tabletop application that supports learning to read for 5-7 years old children. The application trains elementary reading skills using collaboration and a multimodal, collaborative and tangible tabletop environment. The game uses tangible bricks to improve interaction and it uses different strategies to support the learning process – recall, rehearsal and collaboration.

'Pixel Materiali' (Drori and Rinott, 2007) is a tangible tabletop designed to support children creativity in which they can create simple computer animations using physical cube shaped pixels (see Fig 61). Children aged 4-6 year-old were able to easily use 'Pixel Materiali', but collaboration in this installation was not always achieved when tested in pairs of children. Only those who planned in advance the theme of the drawing and agreed their roles in the process were able to do real collaborative work.

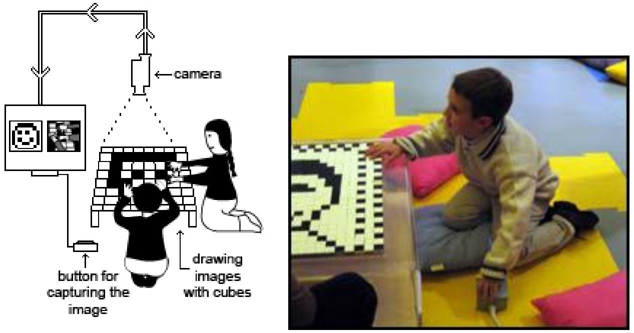


Fig 61: Pixel Materiali tangible tabletop (Drori and Rinott, 2007)

Africano et al. (2004) has been designing interfaces for collocated collaboration from an interaction design perspective oriented to school environments. Their most popular design, 'Eli the Explorer', combined computer augmented toys, with interaction around a tabletop device (see Fig 62).

Fig 62: ‘Ely the Explorer’ game (Africano et al, 2004). Right, tabletop device. Left, Ely toy character.

The game allowed up to three children to collaboratively explore different cultures and social practices through the adventures of a fictional character. The play develops around the story of a group of characters named Elys. An Ely was both a soft toy and a virtual character. On the tabletop screen, Elys are agents that guide the children through the play, giving instructions and interaction feedback. The soft toy is proposed as a tangible link between the digital content and the hardware. Children could teleport an Ely to another country, placing it inside a compartment in the table. Then, children could interact with the virtual Ely using the touch screen on the table, and send it postcard augmented with RFID technology. ‘Ely the Explorer’ is a good example of TUI explorative application in with children are engaged with collaborative playing thanks to the social affordances of a tabletop configuration.

2.3.5 Conclusions

Using digital manipulatives in TUI educative applications enables to transmit new pedagogical contents hard to transmit using only physical manipulatives. But learning will only succeed if these manipulatives transmit concepts in a natural and direct way. Children will benefit of expressive and explorative TUI applications, if they understand the physical affordances of the manipulatives and the meaning of their actions in the virtual environment. The familiarity of children with toys make them a valuable manipulative to build fun and intuitive collaborative tabletop applications reinforcing learning with physical gaming, fun, and social relations. Conventional toys can provide expressive and exploratory interaction in tabletop games, provided by their “presence-at-hand” (children have knowledge of their toys and the objects they resemble), and their “readiness-at-hand” (toys give visual clues of the actions that children can perform with them).

The tabletop applications presented in this chapter, besides assessing the potentials of tangible tabletops in children education, also notice that reinforcing collaboration is a topic that should require further research in future tabletop applications. Tabletop environments are an ideal environment to support face-to-face and close interaction between children, designed applications should also promote them.

Combining toys with the social benefits of tabletop configuration is the research interest of the present thesis, aiming to fill the gap between the manipulative learning and digital technologies used in nurseries and preschools.

2.4 New methodology for measuring tangibility and new classification of Digital Manipulatives

2.4.1 New methodology for measuring tangibility

The Fishkin (2004) taxonomy based on the embodiment and metaphor axis, described in section 2.1.6, is adequate to measure and compare the tangibility of any TUI application. However, as discussed in section 2.1.7, the design decisions taken to create embodiment and metaphor in a Tangible Bit can be associated with a semantic or a direct approach. This section proposes that the quantification of each axis stays the same as Fishkin proposed: “distant”, “environmental”, “nearby” and “full” embodiment, and “noun”, “verb” and “attribute” metaphors, but each axis should be analysed from the design decisions taken to create the application:

- **Embodiment**: How do designers have achieved the embodiment? , how are control and representation of the digital data related with the physical properties of objects?, and which are the human senses used to perceive these properties?

- **Metaphor:** How does user perceive the meaning of the actions carried out in the objects while controlling the digital content? How does user perceive the meaning of the representations of the digital content? Is this based on metaphors rooted on previous knowledge of similar objects or on arbitrary icons and symbols?

The answers to these questions should correspond to a semantic or a direct approach. The design decisions that can be described as a direct design process (see Fig 25) will contribute to the tangibility of the system analysed.

To illustrate this proposal to measure the tangibility, the design of a USB memory stick that can reflect the amount of free memory without needing to connect it to a computer station or another device is following described.

One first logic design decision could be to place a LED array in the frame of the stick giving user perception of the free space (see Fig 63). Full embodiment would be achieved that way.

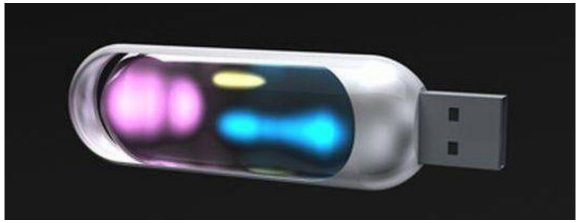


Fig 63: Memory stick with LED output

To associate a meaning to the LEDs in relation with the free memory of the device, a metaphor has to be created. Using a semantic approach, lighting LEDs could mean occupation of the memory. But how do users interpret this? They may interpret that lighting LEDs represent free memory. Users are forced to read the instructions to learn to interpret the LEDs. This metaphor could be improved by drawing a bottle on the frame. Lighting LEDs simulate that the bottle is filling, allowing a more natural interpretation. But, obviously, this metaphor is based on previous knowledge of a similar and well known object (a bottle), and so that, it is semantic.

What kind of design decisions would be taken if a direct approach is used? Dima Komissarov designer took a direct approach to design a memory stick (see Fig 64). The Flash Bag memory stick couples the size and shape material properties of the device to its digital content with full embodiment by getting bigger the memory stick as digital data increases, so user directly perceives the memory occupation of the device not only by eyesight, but also by touch. On the other hand, the Flash Bag does not need any metaphor based on similar objects like a bottle. It gets meaning by using a physical property (size), which human perception naturally connects to the amount of "things" inside the memory.

Fig 64: Dima Komissarov Flash Bag. (Komissarov web ref.).

The method proposed can be used to compare the tangibility of any existing TUI, like the Big Trak toy with the Sketch-a-move design, and also take decisions to create or evolve a "poor" tangible application (like a conventional memory stick), into a rich, intuitive and usable tangible innovation (like the Flash Bag)

2.4.2 New classification of digital manipulatives on a tabletop

Literature on tangible interaction on tabletop devices is scarce, as it is a very recent research matter. Therefore, theoretical models and classifications have not yet been proposed for describing the tangibility of tangible tabletop applications.

Section 2.3.2 presented the "Presence-at-hand" and "Readiness-at-hand" manipulatives. Both visually point out how they should be used, by a semantic meaning associated with them, or by giving visual clues of the interactions they support, respectively. Based on this initial classification, this section proposes a particular generalization of digital manipulatives for tabletop applications, which considers the kind of interactions each one supports as controllers on the application. This classification considers three types of digital manipulatives:

- Token: identical objects which invite users to place them in specific areas of the surface to activate an action on the application.

- Name: Individualized objects whose appearance has meaning by itself; so the user knows its function in the application.

- Token-constrained: Combination of both previous token and named. The object has meaning by itself, but the object can act in the application through some kind of manipulation of a token associated with the object.

The three types of manipulatives and their relationship witj tne "name", "verb", and "attribute" metaphors (see section 2.1.6) are detailed in the next subsections.

2.4.2.1 Token Toys

The term token was first described by Ishii and Ullmer (2004) as discrete physical objects which represent a chunk of digital information (see section 2.1.3). Interaction with token objects on a tabletop device consists of spatially distributing a set of indistinguishable tokens over the active surface. The user immediately receives system feedback as he/she keeps reconfiguring the token distribution on the table. The physical appearance of the token has no meaning to the user, so he/she perceives token meaning as pure action ("verb" metaphor).

Many non-technological children's games could be interpreted as tokens: marbles, caps and all kind of chips in board games. These toys have the same appearance (marbles are all spherical, caps are disc shaped….), and children merely use token toys to perform an action in the game. Game rules do not come from the toys, but from the spatial relations between the toys and the reference frame (table or floor surface).

Furthermore, manipulative tokens are used for first steps in Math with children in Montessory education. Physical manipulation of identical discrete pieces of wood or plastic helps young children to solve their first arithmetic problems.

On a tangible tabletop based on visual recognition, like NIKVision, the system visually detects tokens as blobs, (see Fig 65) without distinguishing each other. The system only needs to track their position on the table and find spatial relations between virtual elements of the tabletop game to trigger the associated action.

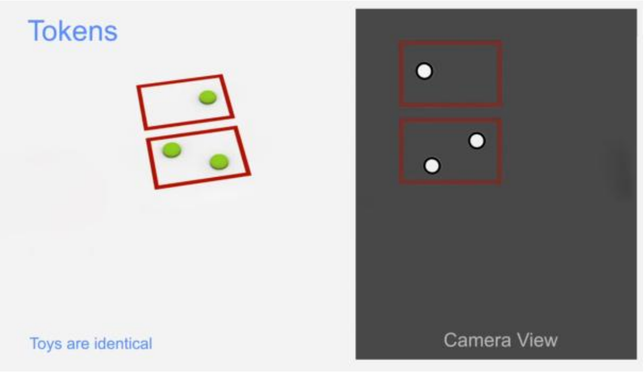


Fig 65: Left: tokens on a tabletop surface. Right: camera views tokens as a circular blob. Tokens get meaning depending on which red square they are placed in.

2.4.2.2 "Name" toys

When the tabletop game requires distinguishing between manipulatives, each one must receive an identification or "name", different from the others. In this situation, the mere presence of the toy on the tabletop (put the toy on the table surface) may have a meaning to the game ("name" metaphor). The identification of the manipulative is associated with its role. Each toy has a different role in the game, and meaning comes from the physical appearance of the toy.

In the same way children identify each "name" toy from its appearance, the system also needs to identify and distinguish each one. In visual based tabletops, each manipulative receives a printed marker or fiducial, which is easily detected and identified from simple topological features (see Fig 66).

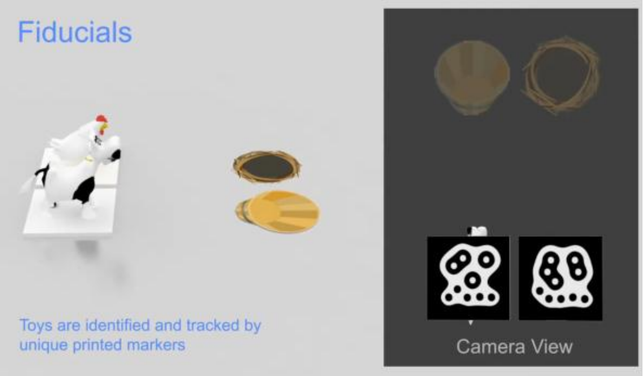


Fig 66: Left: different toys (with different physical appearance) on tabletop surface. Right: the system visually distinguishes each toy by a different fiducial attached to the base of the toy.

2.4.2.3 Token constrained toys

Ullmer et al. (2005) proposed a new approach of tangible interaction by adding artefacts which physically constrain the manipulation of the token. Constraints are confining regions within which tokens can be placed. These regions are mapped with meaning which are applied to tokens located within the constraint perimeter.

For many children conventional toys can be described as token constrained as they are composed of separable or articulated parts which children can move, rotate, detach, push… Token constrained manipulatives should be seen as a symbiosis between token and named, as the constraint is in fact a "named" manipulative, within its physical area, and one or more tokens can be manipulated.

Ullmer et al. (2005) further classified Token-constrained manipulatives depending on the relation established between the token and the constraint:

Associative: tokens can only be placed or removed from the the confines of a constraint. This way, a relationship is established between the token and the constraint depending depending only on the presence or absence of the token (see (see

- Fig 67). It is therefore an associative manipulative where each hole has a meaning in the application. The object itself uses "name" metaphor, but the presence or absence of a token in a particular hole activates or deactivates a particular "digital attribute" (1 or 0) associated with the object.

- Manipulative: tokens are already coupled within a constraint and cannot be removed; tokens can therefore only be manipulated within the confines of their constraint. This way, tokens can only be translated along a linear axis (see Fig 68) or turned on a rotational axis. The relative position or rotation of tokens with regard to the constraint varies an "analogical attribute" of the object.

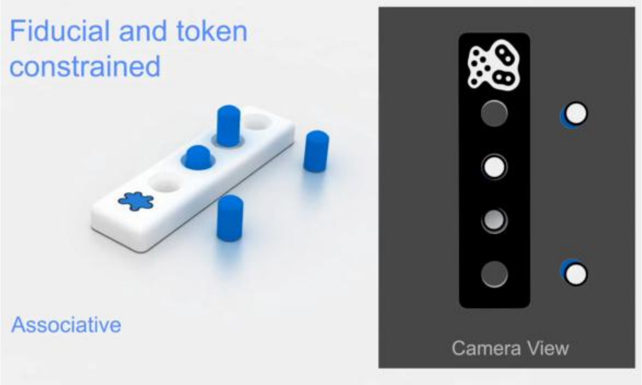


Fig 67: Left: Associative toy composed of four tokens. Right: visual software recognizes the fiducial and then recognizes the presence of associated tokens relative to the tracked position of the fiducial.

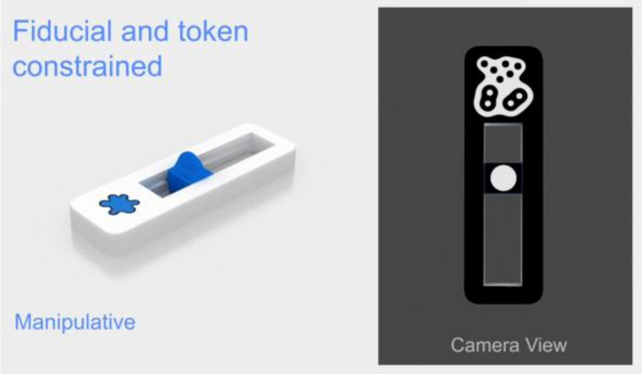


Fig 68: Left: Audio fader toy. Right: toy seen from below the table.

2.4.3 Conclusions

Based on previous classifications and approaches, this chapter proposes a new method to measure the tangibility of any interactive system, based on two axis: Embodiment and Metaphor. The tangibility of each one must be assessed by a direct approach, which reflects how material and user perception have been considered on the design on the system: Those designs that fit with a direct approach will be considered tangible. This method will help to analise present and future proposals based on the Ishii envision of TUI, and also to take design decisions that promote non-tangible systems to get better tangible embodiment and metaphor.

"Name", "verb" and "attribute" metaphors can be associated with any physical control in a tabletop application. In this section, a new classification based on how these metaphors are associated with the tabletop tangible bits has been proposed. This section has outlined a general classification to cover any physical object used as control on a tangible tabletop application based on the physical affordances of the manipulative. This classification can be used to create new digital manipulatives in tabletop applications with meanings based on the physical affordances of the objects as will be shown in section 3.3 and 3.4.

2.5 Children Centered Design

2.5.1 Children Involvement

The Human Computer Interaction (HCI) research community has generated abundant literature about the involvement of adult users in the design of technological applications, but there are not so many references in the case of very young users. Involving children in design is a challenge due to the difficult designer-user communication (Markopoulos and Bekker, 2002), since they cannot yet read, their verbal skills are not fully developed and their cognitive and social development are limited.

The development of the LOGO computer language (Papert, 1977) in the 70's marked the beginning of the research literature contributing to Children-Centered Design (CCD), but there was little interest during the 80's and 90's and research momentum has only recently been on the increase as children have received interest as consumers of new technology.

Druin (1999) proposed a children's role taxonomy in the design of technologies oriented to them. From less to most involvement, children can play the role of users, testers, informants and design partners. Roles with more involvement keep functions from roles with less involvement adding new ones (see Fig 69)

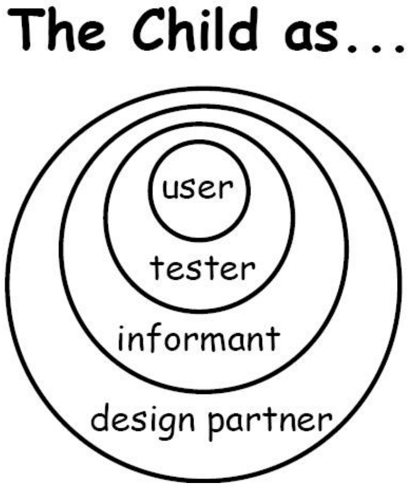


Fig 69: The four roles that children may have in the design of new technologies (Druin, 2002).

- As **users**, children contribute to the design and development process by using the new technology, while adults may use observational evaluation methods. Designers use this role to observe children using existing technologies, and ideate how to improve them; or observe children using the new proposed technology and determine if it is ready to be used as a final product.

- As **testers**, children test a prototype of the proposed technology. Children are again observed with the technology and/or asked for their direct comments and thoughts concerning their experiences. These testing results are used to change the way future iterations of the prototype technology are developed.

- As **informants**, children contribute in the design process at various stages, based on when researchers believe children can inform the design process. Before any prototype is developed, children may be asked about existing technologies, or for input on design sketches or low-tech prototypes. Once the prototype is developed, children may again offer input and feedback giving their opinion.

- As **design partners**, children are considered to be equal stakeholders in the design of new technologies throughout the entire experience. As partners, children contribute to the process in ways that are appropriate for children and the process. While children cannot do everything that an adult can do, they should have equal opportunity to contribute in any way they can to the design process.

Druin emphasized the role of children as design partners in Participatory Design projects, encouraging designers to brainstorm with children from the very beginning of the process using a cooperative enquiry approach in which children and adult designers work together in small groups to brainstorm and discuss "what is wrong" with the existing technologies and ideate and build new low-tech prototypes using basic art supplies (e.g., paper, crayons, clay, string, LEGO bricks, etc.) (see Fig 70).

Fig 70: An example of a "low-tech prototype" for a new storytelling technology using cooperative enquiry (Druin, 2002)

Many researches considered Participatory Design as too ambitious, and many related questions have been subjects of discussion: the precise value of children's input collected through participative methods (Sluis-Thiescheffer et al., 2007) (Mazzone et al., 2008), the quality of the outcome and its various factors (Markopoulos and Bekker, 2002), and the appropriate methods to include children in computer product design (Antle et al., 2003) (Barendregt et al., 2006).

Furthermore, as many consolidated evaluation methods rely on the verbalization of user's thoughts, new proposals to retrieve children's experiences are moving from "what children think about" (Borgers et al. 2000) to "what children do with" (Abeele¸2008) technology. In fact, child involvement based on technology immersion and observation can be of interest to and for preschool children. Toddlers love to explore computer games being the only motivation having fun. Children's attention spans may be limited, but they feel happy showing adults that they are grown-up enough to play with a computer independently and generally they should be able to focus on the same game for periods of 10-15 minutes, time enough for meaningful observations of their using new products (Hanna et al., 1997).

2.5.2 Evaluating with Children

Young children are users of technology with full-right to be involved in user-centred design projects. Well-known evaluation methods for adult users are also applied in evaluation with children, but the special characteristics of their development stage may require important adaptations of these methods, or even discard some of them when working for children belonging to specific age periods.

Related to how they are used, user evaluation methods can be classified as observational, analytical and inquiry evaluation methods (Rauterberg, 1993):

- Observational evaluation methods collect data by observing users' experiences with a product.

- Inspection or analytical evaluation methods rely on the opinion of a group of usability experts. Thus, these methods do not collect data from users' experiences.

- Inquiry methods focus on users' likes and dislikes, needs, and understanding of a product by asking users to answer questions verbally or in written form. Inquiry methods tend to identify broad usability problems or opinions about a product as a whole.

It should be noticed that young children are less able to read, verbalise, concentrate, and perform abstract logical thinking than adults (Markopoulos and Bekker, 2002). Their undeveloped ability for translating experiences into verbal statements, and for formulating compound tasks and abstract task could pose problems to children, as their abstract and logical thinking abilities are not yet fully developed and they are not skilled in keeping multiple concepts simultaneously in mind. Inquiry methods which rely on these skills are therefore not very well suitable for very young children.

Many products for children are still analytically evaluated by adult experts (Buckleitner, 1999) However, "it is not easy for an adult to step into a child's world" (Druin, 1999), and sometimes children show behaviour with a game that are very difficult for adult experts to predict. For example, an error message intended to announce children that they are doing something wrong in the game, might be found so funny for children that they would keep repeating the wrong action just for triggering the error message.

Observational methods seem to be the most adequate for product evaluation with children involvement, but some techniques of observational evaluation that work with adults may not be applied to children. For studies involving children, Hanna et al. (2004) suggest that observing frowns and yawns are more reliable indicators of lack of engagement than children's responses to questions. Read et al. (2002)

propose that children engagement could be measured by observing the occurrence of a set of behaviours including: smiles, laughing, concentration signs, excitable bouncing, positive vocalization, and that lack of engagement could be measured through behaviours including: frowns, signs of boredom (ear playing, fiddling) shrugs, and negative verbalization.

Evaluation methods can also be classified depending on the data obtained from the evaluation as formative and summative evaluation methods (Hartson et al. 2001):

- Formative Evaluation Methods: They are aimed to identify as many aspects of a product that cause users trouble. A usability problem is encountered when the user is not able to reach his/her goal in an efficient, effective, or satisfactory way. Formative evaluation methods have the purpose of improving the product by fixing these problems.

- Summative Evaluation Methods: They are aimed to quantify what is recently being known as User Experience (UX). This concept encloses usability measurements like user efficiency, effectiveness, proficiency, but also subjective measurements of the experience of users interacting with the application: fun and likeability, challenge and satisfaction, which must be coded and rated in order to be used to compare with similar applications or assess the UX of an entire product. Depending of the kind of project, summative evaluation can include other aspects of UX, like physical activity or collaboration that are appropriate for TUI games.

During the design process of the product, evaluation methods will be mainly formative, and their results will guide the iterative nature of the product lifecycle. At the end of the process, evaluation methods will become mainly summative, and will asses that the product has achieved the goals marked at the beginning of the project.

Focusing on evaluation of products for children, formative evaluation methods must look for, not only usability problems, but also factors as pleasure and fun children experience (Pagulayan et al., 2003). Usability and fun are linked closely together: if game has a goal too easy to achieve children might get bored, but if it is too difficult, children may get frustrated. Usability and fun problems will occur during the test and will influence each other, but after the test it may be necessary to distinguish between these different types of problems because they may require different solutions.

2.5.3 Evaluation Methods for Children

Usually, evaluation methods used with children are convenient adaptations of well-known methods used to test with adult users. Most of them rely on user verbalization while the application is being tested or in interviews and questionnaires just after the test. However, verbal and social skills of young children are not well developed to methods rooted in verbalizations and expressing opinion to adult assistants in unusual environments like a test lab. For that reason, most of the evaluation methods adequate to children are indeed variations of adult methods to adapt them to the particular characteristics of children.

Usability Testing: This is the most simple and straightforward method for evaluating products with users. It is an observational and formative evaluation method which consists of providing subjects with tasks and observing them while they perform given tasks (Dumas and Redish, 1993).

Adult facilitators can make quick notes on questionnaires papers previously written with the most important questions to be observed during the test. This method is very easy to arrange with children, as it is no making children to verbalize their thoughts or opinions, and they are just playing with the game for fun. Still, verbalisations or other clear signs of the child are very valuable because they may indicate problems that are likely to go undetected when relying on observations alone. Furthermore, when an observable problem is accompanied by verbalisations or other explicit indications, it is more likely that the problem will be detected by multiple evaluators.

Thinking aloud: Thinking aloud is the most popular usability evaluation method used with adult users (Nielsen, 1993). It is an observational and formative evaluation method. During the test the user is asked to verbalise his/her thoughts while using the product. Young children are often not very good in thinking aloud (Boren and Ramey, 2000). One of the reasons is that it is unnatural to talk to no-one in particular. Because they often forget to think aloud, they need to be prompted to keep talking. Furthermore, prompting children to keep talking when they keep silent is often not very useful. Sometimes children will respond to this request but it is very doubtful whether their response is valid because it seems that they are just making something up to say. After a single response most children remain quiet again. Unfortunately, the amount of self-initiated spoken output in the thinking-aloud method is often limited. Therefore, the reliability of a method that encourages children to express their thoughts while playing with the game will be higher. For that reason many variations of the thinking aloud method is proposed to encourage children to verbalize or express by other ways their opinion:

- **Active Intervention**: Van Kesteren et al. (2003) suggest that the active intervention method is the most effective evolution of thinking-aloud usability evaluation method to elicit verbal comments from children. Adult researcher 'actively intervenes' by asking relevant questions during the game. They found that the researcher can only intervene after the exploration phase. Children need to explore a game at their own pace. In the beginning, they do not know what they are doing and find it annoying when the facilitator asks about the interactions and opinions. Further, thinking aloud together with learning a new game requires too many cognitive efforts. For that reason, the facilitator has to give the child the chance to familiarize with the new game before he asks questions about it. Further, children are inclined to answer what they think the adults would like to hear (Jones et al. 2003). Therefore, it can be useful to record children's behaviours, facial expressions, etc., as nonverbal communication often reveals more information than verbal information.

- **Co-discovering**: The proposal is that children do not play alone, so they have a conversational partner and speak each other what they are doing in the game (van Kesteren et al., 2003). It should be noted that young children often not really co-operate with each other and that pairs may tend to discuss topics unrelated to the product under evaluation (Als et al., 2005).

- **Peer-Tutoring**: While in co-discovering both children learn to play at the same time, peer-tutoring proposes a variation in which one child learn to play first, and later, teach his/her partner how to play(Höysniemi et al., 2003). The basic philosophy behind this is to view software as a part of child's play, so that the teaching process is analogous to explaining the rules of a game such as hide and seek. The peer tutoring approach provides information about teachability and learnability of software and it also promotes communication in the test situation. However, many "tutor" children, avoid to verbalize, and perform teaching just by playing with the game, while his/her partner just observes from behind how to play.

- **Mission from Mars**: This is a sophisticated way to encourage children to Think Aloud adapting the test environment where they play with the game (Dandler et al., 2005). Previously to the game test, children are told by adult facilitators that a contact has been established by martians to the research lab. Researches received some signals, and martians have expressed their desire that some children participate on the test of a new game and give their opinion about it. Children can communicate with martians though voice, or virtual animations on a monitor, or even through a robotic character (see Fig 71). Invisible adult facilitator are in charge of control the martians questions and enquires to children, and can see and hear the test room through videocameras from an adjacent room (see Fig 72). The Mars-method facilitates the discussion between children and researchers offering the possibility of posing very "stupid" questions. The method main strength is that it is a playful inspiring framework for both children and designers and the narrative shared space makes it possible to ask questions that would be impossible to raise in a conventional setting.

Fig 71: Children communicate with "martians" through a robotic character (Markopoulos et al., 2008)

Fig 72: Mission from Mars: adult facilitators observe and communicate with children using videocameras (Markopoulos et al., 2008).

- **Problem Identification Picture cards Method**: It is an observation and formative evaluation method. This method prompts young children to express both usability and fun problems while playing a computer game (Barendregt, 2008). The method combines the traditional thinking-aloud method with picture cards (see Fig 73) that children can place in a box to indicate that there is a certain type of problem (see Fig 74). During the test, the box and numerous picture cards for each problem category are placed on the table next to the computer on which the game is played. Children can place as many picture cards in the box as they like. The children can always ask for an explanation of a card if they happen to forget it. It does not matter whether they use the correct picture card for a particular problem. If the facilitator does not understand why a certain card is used he/she can ask the child for an explanation. Finally, the behaviour of the child with the game together with the picture cards are used to do the actual analysis of the test session. When children can use these picture cards in addition to thinking-aloud they express more problems than with standard thinking-aloud. Children do not just replace verbalisations by picture cards without any verbalisations.

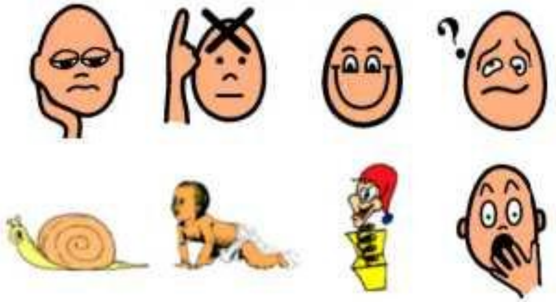


Fig 73: From left to right, top to bottom, the Pictures used for Boring, Don’t know/understand, Fun, Difficult, This takes too long, Childish, Silly and Scary, respectively (Barendregt, 2008).


Fig 74:Picture box (Barendregt, 2008).

Wizard of OZ: More than an evaluation method, the "wizard of Oz" is a setup that facilitates the testing of early and not fully functional prototypes (Höysniemi et al. 2004). Some functionalities of the game, are in fact simulated by a human "wizard" who observes the users and controls the prototypes with a mouse and a keyboard without children being conscious of that. This method has been found useful to evaluate physical and full body interactive applications with functionalities that require lots of efforts to implement. Researchers can combine Wizard of Oz with any other observational and summative method to retrieve valuable information about the children intuitiveness of the movements and manipulations on very earlier prototypes that could not be found testing a fully functional product when there is no existing research on what movements children prefer in different game contexts.

Drawing Intervention: An alternative to thinking-aloud methods not based on children verbalizations is to let children draw their experience after using the game (Denham, 1993). It is an enquire, summative method as drawings are capturing the User experience, and especially, the subjective aspects: fun, enjoyment ... However, drawing need to be coded by adult experts to analise the retrieved UX. Xu et al. (2009) proposed a codification of drawing intervention for TUI applications for children, based on the presence and evidence of specific elements in children drawing (see Fig 75).

Element	Evidence	Score
Fun (F)	Smiling, words (1)	1
Goal fit (GF)	Highly evident (3): Timer on 16 secs, wolf about to catch the smiley face, 'help!!!', oops…	3
Tangible magic (TM)	Evident (2): red block on the reader	2

Fig 75: Child drawing (up) of his experience using a TUI game, and its score by adult experts (down) (Xu et al., 2009).

Detailed Video Analysis: DEtailed Video ANalysis method (DEVAN) (Vermeeren et al., 2002) is based on the structured analysis of video material captured during user tests. This method was developed to detect usability problems in task-based products for adults, so it is an observational formative evaluation method. When used for evaluation with children, this method can be adjusted for the detection of usability and fun problems in computer games. However, using the method is very time consuming and requires including more than one evaluator to reduce the evaluator effect problem (Jacobsen, 1998). The method distinguishes two stages of analysis. In the first stage, observations and verbalization between children and test facilitators are transcribed to an interaction table. In the second stage, the interaction is analised in detail to locate events that indicate an occurrence of a problem. The evaluators have to detect and code the behaviours that may indicate a problem. These behaviours are called "breakdown indications": "any conceptual discoordination between perspectives within and between people, suggesting different ways of characterizing facts and evaluating judgments." (Winograd and Flores ,1986). The result of this stage of the analysis is a list of pairs of time stamps and behavioural categories, the described breakdown indications (e.g. 0.00.13.36, Puzzled). Because there can be multiple breakdown indications for the occurrence of one problem, this list of breakdown indications finally needs to be grouped into problems. For example, a child may say "I don't know how to shoot the spaceship" and then may erroneously click a button to restart the game. Both indications may belong to the same problem, 'Unclear which button is used to shoot the spaceship'. When evaluating computer games for children, both usability and fun problems can occur, and both are important to fix. Fun should be an important factor besides usability; therefore some new breakdown indications to detect fun problems might be needed. Based on the Mallone (1981) videogame taxonomy, Barendregt (2006) proposed a coding scheme that combines DEVAN usability coding scheme with a Fun coding scheme.

Questionnaires: To determine the level of satisfaction of the children with a game they can be asked to rate the game after a test session. It is an enquire and summative evaluation method as children are asked to rate the game tested. Read et al. (2002) designed some questionnaires adapted to children based on a five-point scale Smileyometer (see Fig 76) to measure fun with children aged between 5 and 10. Although young children tend to pick the 'best' face, making it not a very good tool to discriminate between different programs, it can be useful to determine whether there was a change in opinion about the same game after the child acquired some experience on the game after repeated used of it.

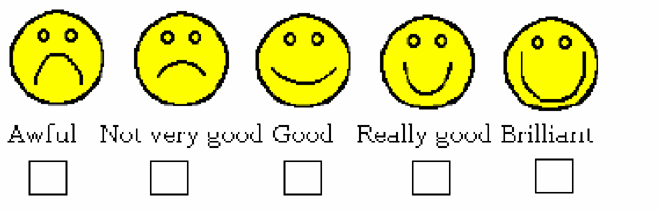


Fig 76: Smileyometer. Children mark the option that corresponds with their opinion of the game (Read et al., 2002).

Laddering: Laddering is an enquire and summative method used to investigate the likeability of a game with children (Grunet and Bech-Larsen, 2005). The researcher asks why the user likes/dislikes something. When the child answers, the researcher will ask 'why' again. This process results in a list of connected elements: 'a ladder'. At the end of the ladder, the personal value(s) of the user will be revealed. This method is appropriate to know what children find the funniest and the most boring aspect about a game and why. Since children have difficulties to abstract their experiences and opinions, it is not always possible to reveal their fundamental values.

Structured Expert Evaluation Method (SEEM): SEEM is and inspectional formative methods in which a group of adult experts analyse the game answering a set of question relating to four categories of the game from two perspectives: usability and fun (see table 1)

Table 1: SEEM questionnaire (Baauw et al., 2004)

Category	**Usability questions**	**Fun questions**
GOAL	Can children perceive and understand the goal?	Do children think the goal is fun?
PLANNING ACTIONS	Children perceive and understand the actions they have to execute in order to reach the goal?	Do children think the actions they have to execute in order to reach the goal are fun?
PHYSICAL ACTIONS	Are children able to perform the physical actions easily?	
FEEDBACK	Can children perceive and understand the feedback (if any)?	Is the negative / positive feedback motivating?

To carry out the evaluation, the game has to be decomposed on minigames, each one having only a goal to be achieved by the children. The SEEM questionnaire is answered by experts analysing each minigame individually. SEEM provides with a detailed analysis of each sub goal of a game, detecting any fault and considering the coupling of usability and fun elements. But children are in fact not involved in the evaluation and expects may not predict some behaviours of children. Combining a SEEM method with any other observational method like thinking-aloud methods or videoanalisys, will provide at the same time, children reactions and opinions while using the game.

2.5.4 Conclusions

Choosing a method for an evaluation session depends on many variables: the age of children, the test environment, and also the stage of the development lifecycle of the product. However, the main thing to remember, which also is the main difference between testing with adults or children, is that children are testing the games just for fun. Children must not get the impression that they are been tested instead of the game. Thus, observational methods are the most adequate for children. While verbal comments are still the most valuable information a child can give during a test, pushing them to talk will result on the opposite effect. More that structured methods to elicit verbalization from children, friendly environments like they own classroom, and the possibility of playing with their friends, will promote natural verbalization. When children realise that they are not been tested, but they are the tester of a new game, they get conscious of their important role, and will be prone of giving their opinion and suggestions to adult designers during the test.

There is no doubt that, nowadays, any research of innovative technologies for children must have children involvement as the core of the project. However, this does not mean that all the work must focus on co-work with children, because there is the risk of having carried out a nice research on children involvement, with the only result of many nice hand-made low-tech prototypes and no realizable or practical new technologies ready to revolutionize children's education or entertainment.

That does not mean that children involvement is not practical, or it would be only useful on final stages of product development. Children can be testers and user of even very early prototypes. Test session grounded on simple observation of children, could generate valuable usability and user experience income to designers that will guide all the process of creation of innovative technologies for children that will success in achieve children expectations and necessities.

While the objectives of doing evaluation with children keeps the same (formative evaluation to locate breakdowns to be fixed, and summative evaluation to retrieve global user experience), methods are adapted to retrieve this data by considering that children are not really testing a product, but having fun playing with it. This way, communicating what they are thinking or expression opinion must be a fun and attractive activity to them. Methods like "mission from Mars", "Drawing Intervention" or the "Fun toolkit", are fun versions of "thinking aloud".

3 NIKVision

This chapter describes the work carried out to design and develop NIKVision, which is composed of a tangible tabletop prototype and a set of games and toys oriented towards preschool environments.

Section 3.1 describes the design lifecycle followed during the design process of NIKVision in very general terms. The lifecycle is divided in three main stages (feasibility, prototype and development), which is also the narrative structure of the next two sections.

Section 3.2 gives details about the design lifecycle of the tangible tabletop device and its evolution, with the information retrieved from using it in nurseries and schools.

Section 3.3 goes in depth into the creation of a tangible Farm game designed to explore the potentials of NIKVision tabletop. The details of the many test sessions carried out with children offer a complete Children-Centered Design case study.

Section 3.4 goes beyond the tangibility used in the Farm game, by creating a new set of games and toys rooted in the new classification proposed in section 2.4. These games are used to explore collaborative behaviours in children playing with in a tabletop device.

Finally, section 3.5 concludes the chapter by outlining the results obtained from developing NIKVision and the lessons learned from this experience.

3.1 NIKVision Lifecycle

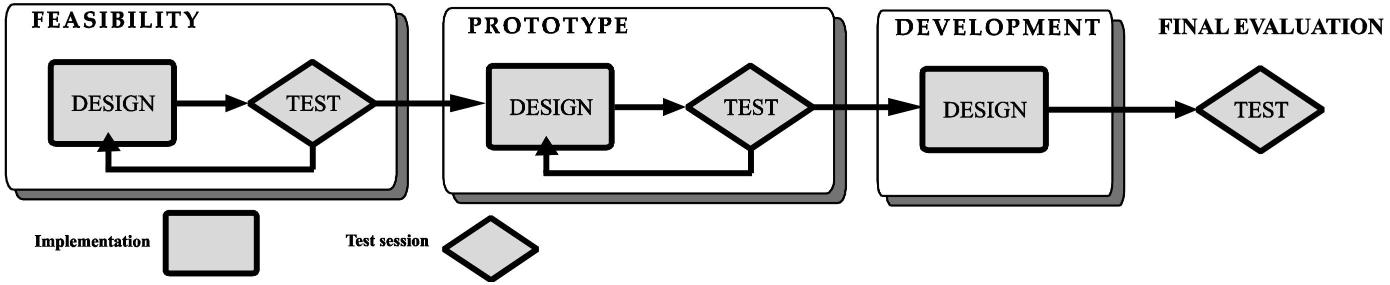


Fig 77: Usability Engineering Lifecycle used to develop NIKVision.

Stringer et al. (2004) noticed "that TUIs are particularly well-suited to a process of frequent, incremental and iterative design. This is because many of the most important aspects of a TUI – those around integration with the physical context of use – can be tested using low-tech prototypes which can be built quickly and cheaply". The engineering lifecycle of this work is based on a cascade of three main stages (see Fig 77) based on the usability lifecycle proposed by Mayhew (1999). It is divided in three main design stages:

1. Feasibility: design work focusing on observation of user needs and shortcomings of the present technologies, and on ideation and fast prototyping of early concepts of technologies with involvement of the users who this technology is intended for.

2. Prototype: Creation of a non-complete but functional product whose evolution is guided by frequent test sessions, with users using formative evaluation methods which allow to compare different prototype versions and choose the most adequate to start a new design iteration.

3. Development: The prototype becomes a final product, completely functional. Methodologies are oriented towards detecting usability problems during test sessions, and correcting them in the next design iteration.

The cycle takes users into account and reflects the iterative nature of the design of interactive technologies. Much of this iterative development is focused on the early detection of usability and design problems using structured evaluation methods in planned and frequent test sessions, followed by successive "go-backs" in the development process to resolve them.

From the beginning of this thesis, the involvement of children throughout the process has been one of the main objectives. However, this involves many challenges. As outlined in section 2.5, methods based on users verbalizing their thoughts and opinions about the product tested are not adequate for young children. It is a very important task to find children-friendly evaluation methods to retrieve valuable data to help in the evolution of NIKVision. Testing in the lab also brings many problems. Young children outside their usual environments may be reticent to play comfortably and to show natural behaviours. Schools and nurseries are a more adequate testing environment, and also provide bigger groups of children to test. On the other hand, carrying out test sessions in schools involves disruption of teachers' and children's routines, and also many ethical questions need to be considered, like obtaining permission from parents or tutors.

The ChiCI Group of University of Lancashire in Preston (UK) has experience in CCD methods and supporting researchers in the evaluation of innovative technologies. They helped in planning and arranging all the test sessions of NIKVision, which were performed in nurseries and schools in the local Preston area. The group has agreements with many local schools and nurseries in the Preston area, and keeps records of all parents who have given their consent to letting their children participate in the test session, or be photographed or filmed. Therefore, the children's involvement was made possible by the ChiCI group, which helped in the evaluation and also helped to find and apply the most adequate CCD methods.

3.2 NIKVision Tabletop

3.2.1 Introduction

The design process of the NIKVision tabletop device was an iterative process based on the previously outlined three stages:

1. Feasibility: The work on this stage began with looking for inspiration in nurseries, and it was followed by quick prototyping of the simple concepts that emerged from this inspiration.

2. Prototype: Once the concept had assessed it viability, it evolved to a functional device that iteratively was refined and augmented with more capabilities.

3. Development: The prototype device was aimed to recover data about the optimal design of the tabletop device. Once this data had been recovered, a new device was built, this time aimed to be a final product to be installed and used as an activity in nurseries and schools.

The following subsections describe these stages and give details of the data recovered from the tests carried out with children playing with the tabletop.

3.2.2 Feasibility

Computers are already present in most nurseries. However, after visiting several nurseries, it was observed that digital technologies are not really integrated in these environments. Play areas in nurseries are usually distributed across the room in such a way that children can easily move from one activity to another, taking part in the activity in little groups (see Fig 78). Meanwhile, the computer is usually set aside in a corner of the nursery, apart from the rest of the areas, and its use is at the discretion of the teacher, who uses it only occasionally with one or two children who are split up from the rest of the classroom (see Fig 79).

Observing this situation, the goal of NIKVision is to design an innovative computer device which can be integrated with the rest of nursery activities. Furthermore, it has to meet the requirements of:

- Not using expensive or uncommon technologies,

- Being easily transportable and installable in nurseries,

- Children-proof designed and built.

Fig 78: Typical nursery environment, with play areas distributed across the floor or in small tables.

Fig 79: Computer station in the nursery is kept apart from the other activities. Up to two children can sit on the table, but really only one is playing the game.

The first concept for this NIKVision device was a "floor interactive surface", which was made mainly from cardboard. The playable area on the floor was defined with a big white piece of cardboard where children could play by manipulating toys (see Fig 80.1). This area was visually recorded by a videocamera (see Fig 80.2) placed overhead from the playable area. Visual recognition algorithms running on a PC (see Fig 80.3) analysed each captured frame to detect the toys over the surface. A conventional monitor (see Fig 80.4) placed in front of the children showed the videogame virtual environment controlled with the manipulations of the toys. With this concept in mind, a very simple prototype was built using basic materials and very accessible technology in order to study its impact with children.

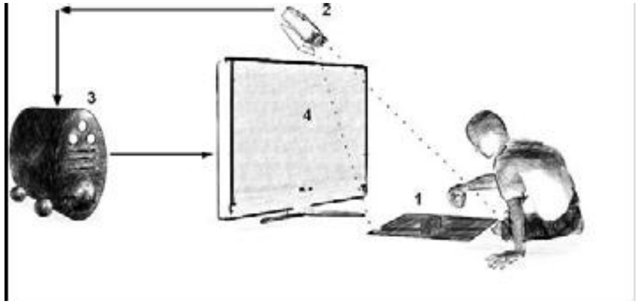


Fig 80: First outline of NIKVision tabletop.

3.2.2.1 Visual recognition software

Despite the simplicity of the physical construction, some sophisticated visual recognition software was developed in order to track objects on the play area. The algorithm represented in Fig 81 detects objects on the surface by:

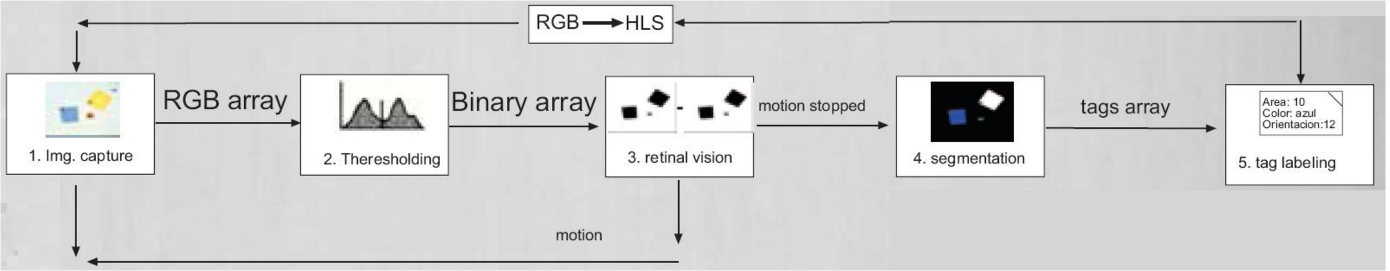


Fig 81: Early visual recognition software algorithm for NIKVision.

1. Retrieving images from the videocamera,

2. Converting them to binary (black and white) through a process of automatic thresholding,

3. Comparing them to previous images in order to detect motion,

4. (If no motion is detected) segmenting the image in blobs (each blob is a surface region where a toy has been placed)

5. Characterizing each blob with size, colour and orientation attribute

Different toys are identified by colour. Size and orientation is used to give the same size and orientation to the virtual representation of the toy on the monitor.

After the visual recognition process, the computer has full knowledge of the objects placed on the playable surface. This can be used to control the virtual objects in a 3D environment displayed on the monitor in front of the child. These objects will appear and move according to the manipulations of the cardboard pieces on the floor.

3.2.2.2 Farm toy

Based on this configuration, and inspired by popular wooden farm toys (see Fig 82), a virtual farm was recreated in a 3D environment on the monitor and farm animals were drawn on the coloured cards (see Fig 83) (pigs, cows, sheep and hens). In this way children were able to populate the virtual farm with virtual animals by placing colour cards identified with animal drawings (see Fig 84).

Fig 82: Le Toy Van” wooden farm toy.

Fig 83: Above: physical animal toys as colour cardboards. Below: Virtual representations of the toys.

Fig 84 Low-tech prototype of NIKVision tested by a 3 year-old child.

3.2.2.3 Occlusion problems

This very early NIKVision prototype was tested in our lab with a couple of 3 year old children. They became immersed in this new technology very quickly, but important problems with the floor configuration were evident. When children placed animals on the desktop floor, their bodies occluded the previously placed cards because the camera was capturing the surface from above. The retinal vision stage of the vision algorithm (see Fig 81.3) was not helping the situation. Children were continuously moving into the visual area of the camera, so feedback hardly took place, and children lost attention with regards to the monitor. Only when children were told to move away from the playable surface did they pay attention to the new animals on the monitor. It rapidly became apparent that these occlusion problems would pose significant handicaps to our objectives for NIKVision. In addition, the children were not very happy with the fact that the graspable objects were limited to coloured cardboard with an illustration in the middle. They tried to play with their own toys on the playable surface and they expressed frustration that these did not have 3D representations on the monitor. These problems were a notable limitation of the system and that showed that it needed to be redesigned. It was necessary to redirect the video-camera tracking in order to avoid user occlusion, and to incorporate some kind of conventional toys.

3.2.3 Prototype

To get rid of the occlusion problem in NIKVision, components of the device had to be redistributed in order to prevent children from blocking the view of the camera. In the new design, the camera was moved to view the playable area not from above but from below. Thus, the early NIKVision design based on floor interaction evolved into a tabletop device (see Fig 85) by adding a table. All the vision components of the device were placed inside the table, so children would never block the camera view when manipulating the toys on the table surface. The new design, besides solving the occlusion problem, offered new possibilities:

1. In the new configuration, it was easy to use any conventional toy by simply attaching a colour cardboard to its base.

2. By placing a translucent surface on the table, an active image could be projected onto the table surface by placing a video projector at the back of the table and a mirror to reflect the image under the table surface. This way, near embodiment could be achieved in NIKVision, giving image feedback on the same place where toys were manipulated.

3. As long as table height is maintained low enough, a table configuration is an ideal setup to support a group of children playing around it without continuously invading the play area with their bodies and obstructing each other.

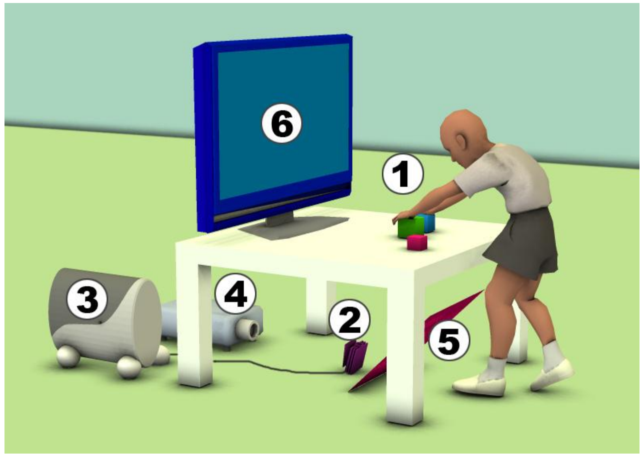


Fig 85: Table based redesign of NIKVision. (1) Conventional toys. (2) Camera connected to (3) computer running vision algorithms. (4) Video projector. (5) Mirror. (6) Computer monitor.

3.2.3.1 Moving to a table configuration

Using the same components as the floor based NIKVision, the new configuration was easily prototyped using a conventional low table with a surface of 70x70 cm and 50 cm high, with a transparent surface (see Fig 86).

Fig 86: First test of NIKVision prototype using a conventional table with a transparent surface.

In order to test this prototype with children, the table surface was covered with a diffuser paper. This way, children did not see inside the table, and they were not blinded by the light placed below the table to give light to the colour identification cardboard attached to the base of the toys (see Fig 87). In a lab test with a couple of children, the new design totally overcame the occlusion problems observed in the previous floor design. Children could manipulate the toys on the surface, receiving immediate and robust feedback on monitor. This time intervention from adults was not needed, and children could play for their own long period of time, controlling the virtual animals with the physical toys. But when finally they felt tired of playing, they were curious about what was under the table, and tried to explore and move table components such as the mirror or the camera.

Fig 87: First test of NIKVision table with a 3 year-old child.

3.2.3.2 Covering table walls

The next design decisions were aimed at covering the interior of the table (see Fig 88). This way, children were impeded to go inside the table and move the components. Covering the table with white walls improved the diffusion of light inside the table.

Fig 88: Covering the sides of the table improved the diffusion of light. Lamps were placed on the sides of the table, just below the frame of the table surface.

One side of the table is used to position the monitor, and this side is also used for the video projector. To gain projection distance from projector device to table surface, a conventional mirror is placed inside the table to redirect projector light to the table surface (see Fig 89).

The final appearance of the prototype is good enough to be attractive to children (see Fig 90), while still easily mountable and dismountable in preschool environments for testing purposes.

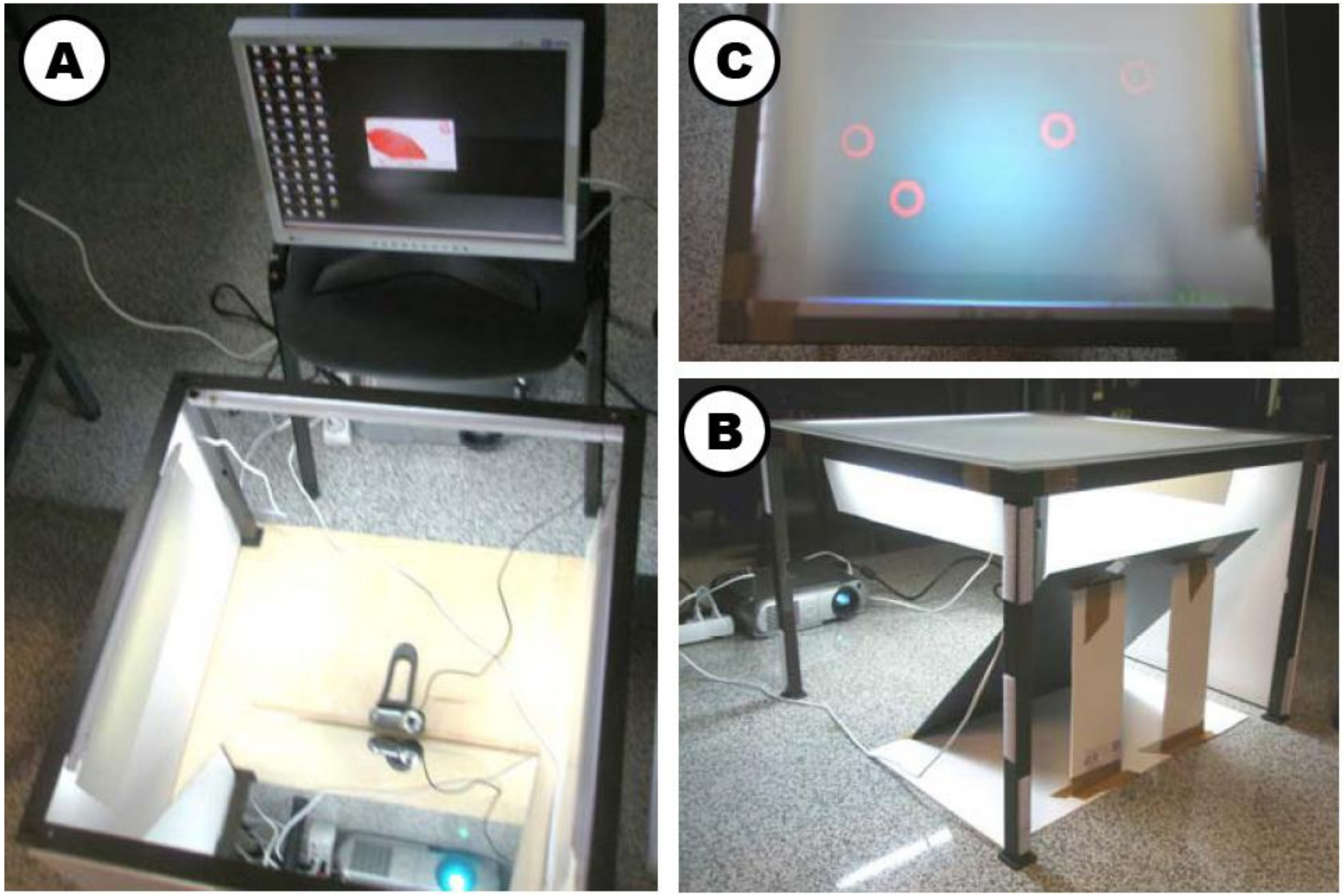


Fig 89: A: camera placed in the middle of the table base. B: projector casts light from below the monitor and image is reflected on a 45º mirror to redirect to table surface. C: virtual image is projected on translucent table surface.

Fig 90: Final design of NIKVision tabletop prototype.

This prototype was again tested in lab with children. Many problems of interference appeared between the colour cardboard attached to the base of the toys and the virtual image projected on the table. Colour cardboard was confused with image projection, which brought about many false toy detections, whilst real toys were not detected because they were blocked by image projection. During initial trials, image projection was limited to very simple and sparse shapes to avoid confusion with toys. Also, projector light had to compete with lamps inside the table, so the image generated on the table surface had very low luminosity and children showed difficulties distinguishing the projected images (see Fig 91).

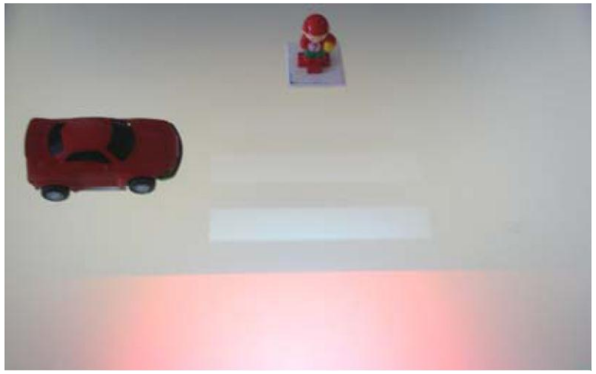


Fig 91: A street with zebra-crossing is barely perceived because it competes with light inside the table.

3.2.3.3 Using infrared illumination

To get rid of these problems, NIKVision was redesigned to use infrared (IR) lamps. Replacing conventional lamps inside the table with special 850nm IR lamps enabled us to give enough diffuse illumination inside the table to illuminate the base of the toys, but as this light wavelength is not perceived by the human eye, users perceived the inside of the table as being in the dark and saw only the projection light, which is now perceived at maximum luminosity. Changing to IR illumination meant to change the filters of the videocamera, as it only had to receive light on the 850nm wavelength. When blocking the rest of the light the camera did not receive an image from projection, so it did not interfere with the image of the toys. As a collateral effect, the tabletop device became more robust under any environmental light conditions, since the camera did not receive any other light except on the 850nm wavelength, which most conventional room lamps use to emit. The result was that any graphic design was able to be projected, improving the visual quality of the feedback on the table surface and showing a rich 3D and animated farm environment (see Fig 92).

Fig 92: Rich graphics projected on the table surface can be perfectly perceived on the table surface provided by using IR lamps inside the table.

3.2.3.4 Using Reactivision fiducials

Although the IR light redesign solved all image projection problems, the visual algorithm based on colour recognition became useless. Colours are on the visible light spectrum, thus the camera with IR filter was unable to see any colour. In consequence, the tracking of toys could no longer be based on colour. As an alternative, it was decided to use fiducial recognition software to substitute the colour recognition software. Fiducials are black and white printed which patterns can be seen using IR light. Specifically, Reactivision framework was chosen (Kaltenbrunner, 2007), as it is widely used for fast and easy prototyping of tangible tabletops. Reactivision functionalities have been widely used to prototype games for NIKVision, and also new functionalities have been implemented due to specific requirements in some games, as described in annex 2.

Reactivision fiducials are based on the topological features of the printed markers, and each pattern is identified by Reactivision software, also giving the position and orientation of the fiducial on the table. In this way the colour cardboard was replaced by Reactivision fiducials attached to the base of the toys (see Fig 93). This redesign resulted in more robust and fast recognition of toys, with position and orientation tracking. Also, the game could use more different toys, as there can be more than 400 Reactivision fiducials, giving more than enough identifiers for toys in the game.

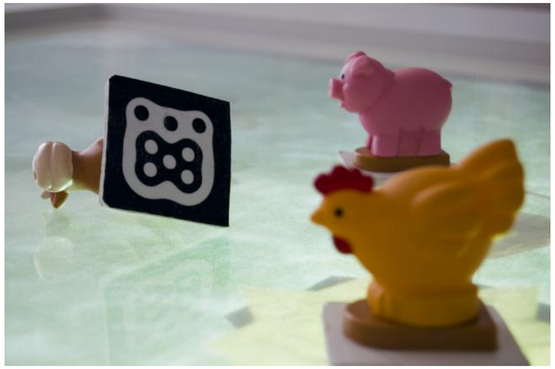


Fig 93: Reactivision fiducials attached to the base of conventional toys.

At this stage, a fully functional prototype was achieved: robust, transportable and easily installable. The table furniture was dismountable, and all the set fitted in a flat box. This way, the NIKVision prototype could be easily moved from our lab to the nurseries or schools ready to be tested.

3.2.4 Development

During these tests several problems arose. The limitations detected in the prototype can be outlined in the following points:

1. The usable area of the prototype table surface (approx. 60x40 cm) was insufficient to support more than 2 or 3 children interacting with the games at the same time. A larger interactive area will make interaction more comfortable and support more children interacting at the same time.

2. The height of the prototype table (50 cm) was adequate for 3-6 year old children, if they play standing up, but not playing on their knees, which was a more conformable pose for children. Lowering the table will enable children to play with NIKVision in that pose, supporting children playing for longer periods of time without tiring.

3. The thin and weak walls of the NIKVision prototype were continuously hit by children's feet and knees when they were trying to play very close to the table. This was not comfortable for children, and even produced malfunctions on the system, as when hit very hard the components inside the table were displaced, offcentering the projected image and moving the camera. More robust walls should protect the inside of the table, and should be designed to enable children to get close to the table without hitting the table walls.

These are not important for occasional use, but as the table was intended for permanent activity in a nursery or classroom environment, the prototype was not adequate.

The first and second points are inverse related. Increasing the area of the interactive surface would require more distance from the videocamera and videoprojector to the surface. But the second point required decreasing the height of the table. In consequence it was needed to design a way to gain distance from the surface to the camera and videoprojector, not lifting the surface, but combining two decisions:

- Moving these two devices away from the table, gaining distance.
- Using wider optics on the camera and projection to achieve better short throw distances.

First, the projector was lifted from the floor using a stand, gaining extra distance from the surface without placing the projector far away from the table (see Fig 94). The projector was fixed on a nearly vertical stand, and the light reflected on the floor of the table, which is a mirror, reflecting the image onto the table surface.

Second, the camera was placed in a similar way: it was placed higher, at the back of the table, looking nearly vertically to the mirror floor of the table (see Fig 95). So, in this new redesign of the table, the camera is seeing the table surface reflected in the mirror.

With the new distribution of the camera and projector components, the usable surface area of NIKVision increased to 110 cm. x 95 cm. This enables up to five children to use the table at the same time without struggling each other. Also the height of the table could be decreased to 45 cm, which is only 5 cm less than NIKVision prototype, but enough to be used by young children.

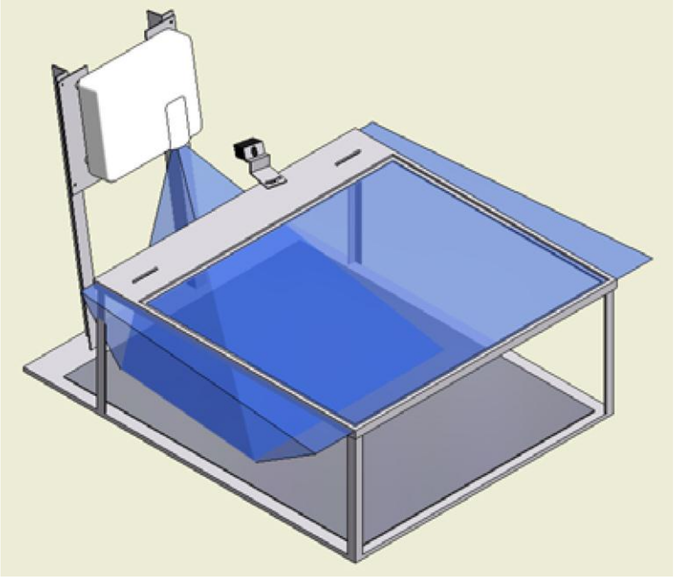


Fig 94: Graphic simulation of image projection in the new tabletop design.

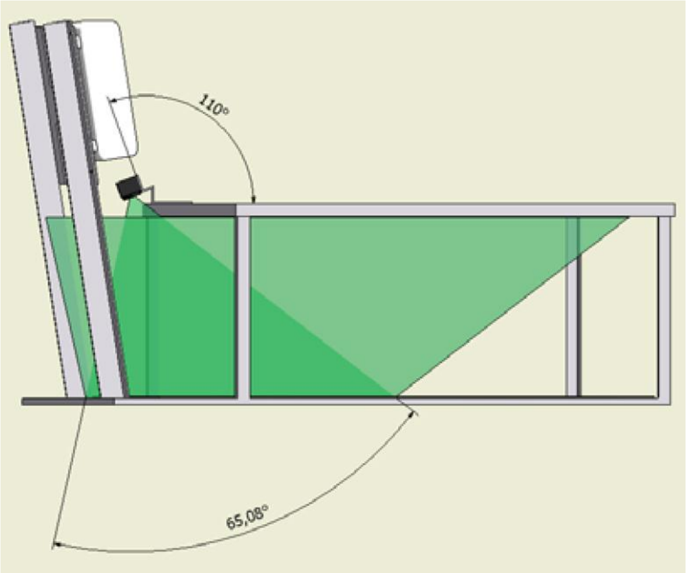


Fig 95: Graphic simulation of camera seeing table surface from reflection in the mirror placed on the floor of the table.

In order to avoid children hitting the table walls, the design included a depression in the lower half which gave room to feet and knees.

Thus, during the development stage, a bigger and more robust NIKVision tabletop device was built, able to support up to five children playing at the same time, and robust and endurable under long and frequent use in a classroom environment.

In Fig 96 the final design of NIKVision is shown. It is heavy enough to not be easily displaced when children actively play around it, so it is ideal to be installed permanently in a nursery or school and let children play autonomously with it.

Details and blueprints of the final design of the NIKVision tabletop are given in annex 1.

Fig 96: Final design of NIKVision tabletop. Left: front view with table surface projection and 3D environment on computer monitor. Right: back and inside of the table.

3.3 NIKVision Tangible Game

3.3.1 Introduction

The engineering lifecycle followed in the creation of the NIKVision games has considered the particularities of the design of interactive products based on natural interaction, through children's involvement during trials of the games. Test session were not only planned to retrieve early formative issues of usability and user experience, but also aimed to retrieve children's natural mental models of interaction with toys on a tabletop device. Fig 97 reflects the NIKVision games design lifecycle divided into three main stages:

- The **Feasibility** stage comprises the exploration of issues and concepts to bring natural computer interaction to children’s activities in nurseries and classrooms. During this stage, work focused on looking for inspiration, by observing children using computer educational games on the one hand and playing with conventional toys on the other. New concepts of games which would combine these two approaches emerged.

- The **Prototype** stage reflects the many design questions and the final decisions taken during the creation of an interactive game for the tabletop device. Prototyping a TUI is not only software coding, but also prototyping the “physical computing”: children informed of the design of the natural gestures of children interacting with the toys. Also, children were involved in the design of an autonomous character which guided them through the tasks of a Farm game.

- The **Development** stage describes how the game was finally refined and fixed.

- The summative results of the **final evaluation** process are also detailed.

From Feasibility to Development stage, the design of NIKVision toys and games has evolved with the involvement of children at each stage.

The following sections describe these stages and discuss the specific situations and methods used to capture and analise information from the test sessions.

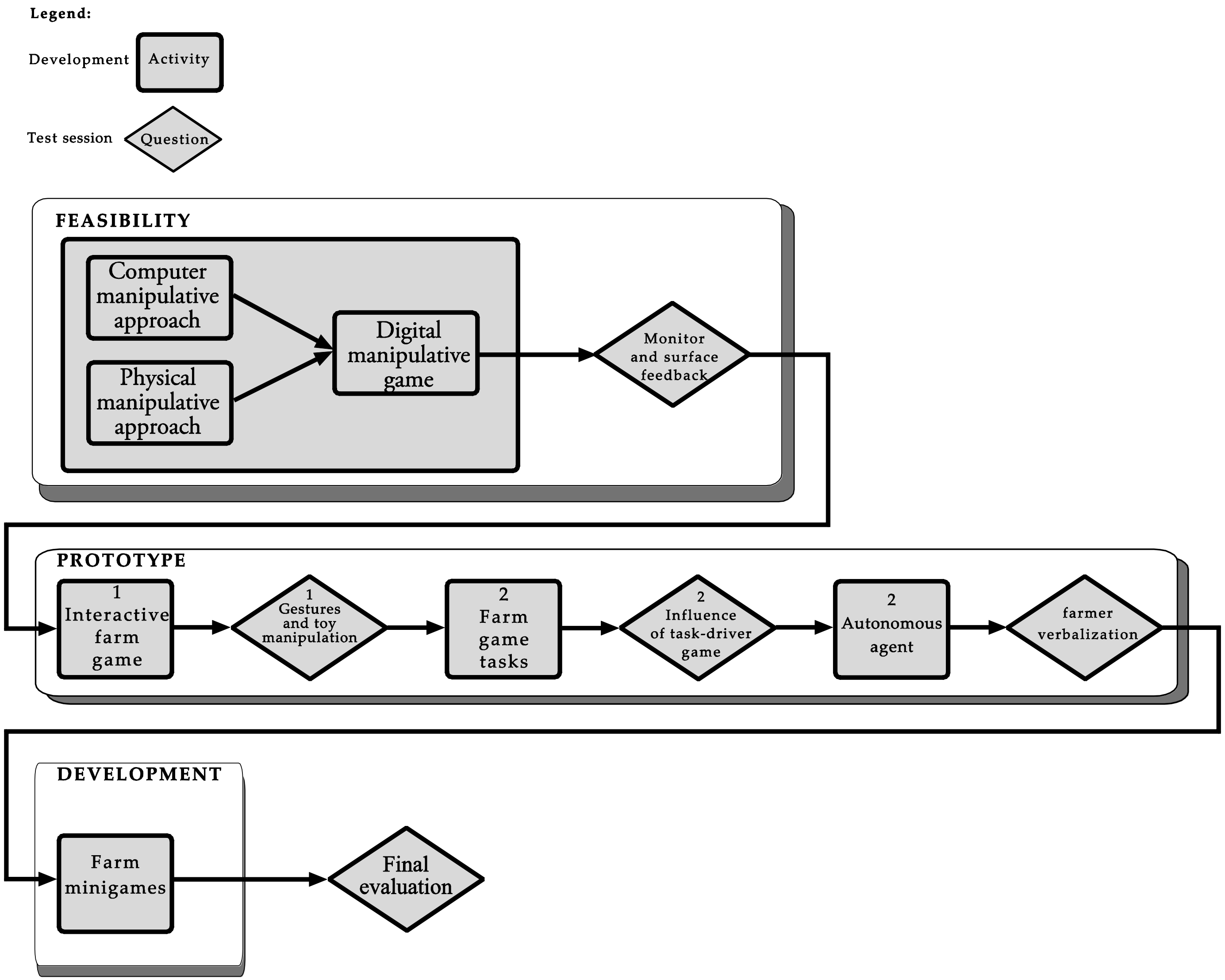

Legend:
Development
Activity
Test session
Question
FEASIBILITY
Computer manipulative approach
Physical manipulative approach
Digital manipulative game
Monitor and surface feedback
PROTOTYPE
1 Interactive farm game
1 Gestures and toy manipulation
2 Farm game tasks
2 Influence of task-driver game
2 Autonomous agent
farmer verbalization
DEVELOPMENT
Farm minigames
Final evaluation

Fig 97: The cascade lifecycle of the NIKVision project.

3.3.2 Feasibility

Tangible tabletop game concept ideation was based on an appropriate combination of the “digital and physical” nature of tangible interfaces. Getting inspiration for a new application based on digital manipulatives could be from any of two approaches (see Fig 98): observing a conventional physical activity and then figuring out how to upgrade it with computer augmentation; or observing a computer activity for children and then seeing how to translate computer manipulatives to the physical world. The result from any of the two approaches is an interactive application in which digital manipulatives are the controls of the digital system. How children perceived the state changes in the digital system through image output on the tabletop was the research subject of the test session planned for this design state.

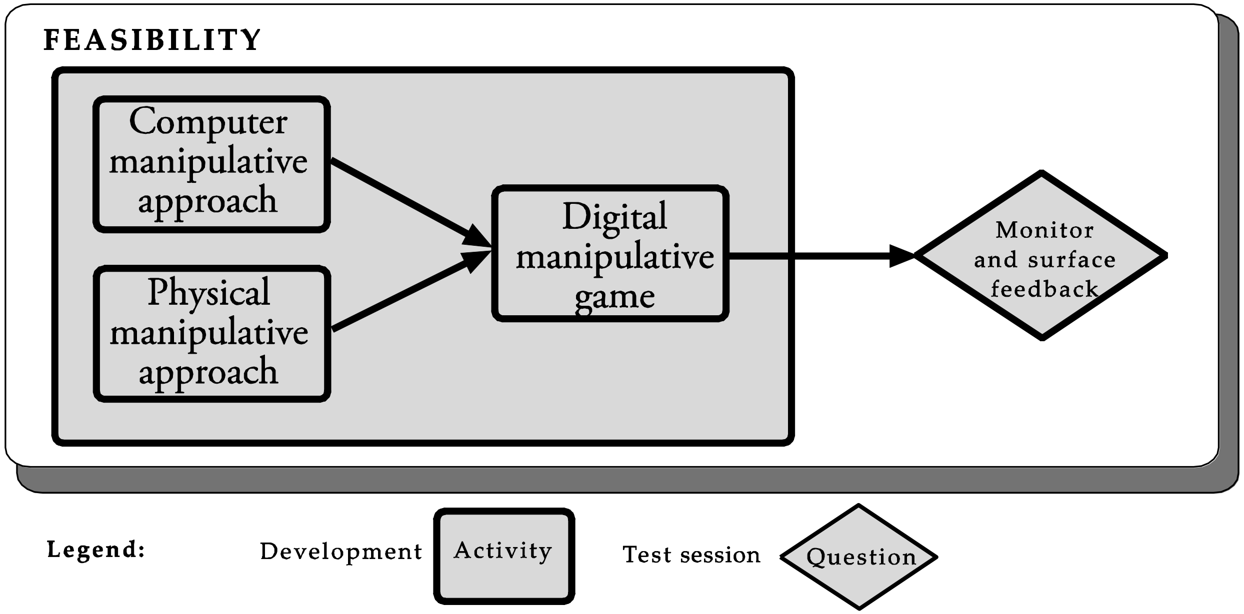


Fig 98: Feasibility stage

3.3.2.1 Computer manipulative approach

Designers can start from a computer manipulative concept (pre-existing multimedia game based on manipulation of virtual objects using keyboard or mouse) and translate it using physical embodiment. This way, computer manipulatives in the multimedia game are recreated as tangible bits which children could use to control the computer world of the game.

This method was followed to create a tabletop game starting from a pre-existing "Cross the Street" educational computer game where children had to use the mouse to manipulate a cartoon character to guide it across a street (see Fig 99). The videogame from Otto's Playland teaches toddlers the rules to cross a street. They have to drag the chicken character (computer manipulative) with the mouse, to the other side of the street when the traffic light is green.

During a test session of this game in our lab with a couple of children, it was observed that this game did not support more than one child playing at the same time. Also mouse drags and arrow symbols on the monitor were very confusing to children who were more worried about discovering how to move the chicken than about the traffic rules.

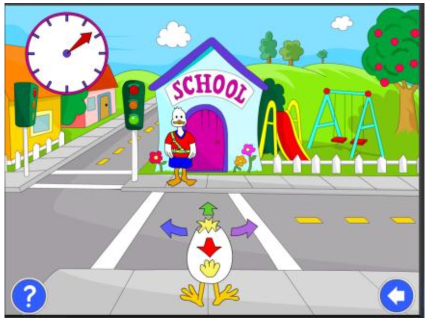


Fig 99: Computer manipulative "Cross the street" game. [Otto's Playland].

This test was the basis for the ideation of a tabletop tangible version of the "Cross the Street" game, adapting it to a digital manipulative approach using Playmobil™ toys and plastic cars (see Fig 100). Only the manipulatives were translated to the physical world. The street environment was kept in the virtual world, using a 3D street on the tabletop monitor. Special care was taken in the design of the virtual environment. As physical toys were associated with a 3D virtual toy on the monitor (3D pedestrian and car), the 3D scene street environment was designed as if it were a real toy street, simulating that it was made of wood and cardboard. Also the toys have nearly identical replicas in the virtual world (see Fig 101).

Fig 100: Digital manipulatives of the “Cross the Street” game for NIKVision tabletop.

Fig 101: 3D virtual scenery of the “Cross the Street” game.

This new concept was also tested by the same children in the lab, and they were observed while playing. Children physically dragged pedestrian toys on the table surface, and they saw the virtual environment of the street on the monitor in which a virtual representation of the toys replicated the physical movements. Having more than one pedestrian toy, more than one child can play with the game at the same time. Provided that the original game was extended with car toys, children could take different roles (pedestrian or car) and coordinate their actions (see Fig 102).

Fig 102: Two children playing with the “Cross the Street” game on NIKVision, taking different roles (car and pedestrian).

3.3.2.2 Physical manipulative approach

A different approach for creating tangible tabletop games is to start from a conventional physical manipulative game and design computer augmentation which would enrich the toy with image and audio feedback. This was used to create a tabletop game for NIKVision based on one of the most popular traditional toys: a wooden farm toy (see Fig 103). This kind of physical toy encourages children to create their own stories through the interaction of manipulative toys with the toy scenery (the farm). The interaction of children with the farm toy can be described as “expressive” as cited in section 2.3.3.

Fig 103: "Le Toy Van"™ wooden farm toy

When redesigning the toy as a tabletop computer game, some elements stayed physical (the animal toys) and others were translated to the digital system (the farm). But the game had to provide the same kind of expressive interaction to children. In order to do that, the 3D scenery on the monitor was modeled very similar to the real toy. Dragging animal toys on the table surface was reflected in the computer monitor, where a 3D virtual toy replicated the same movements in the virtual farm scenery (see Fig 104 above). Also, interactive virtual elements in the shape of bushes were placed in the yard. When an animal toy was placed near a bush, it triggered shaking animation and sound. Using projection on the table surface, the bushes were mapped with icons to help children to locate them in the monitor (see Fig 104 below). Children could place toys on the bush icons on the table surface, and they saw on the monitor the 3D virtual bush being shaken by the animal.

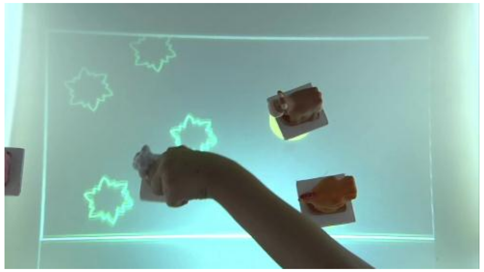


Fig 104: Tabletop Farm game first concept with interactive bushes. Above: Monitor output. Below: Table surface image output.

At this moment, an important research question was set out: how both image outputs (monitor and table surface) influenced the usability of the game and how the children perceived and used them.

This time, NIKVision was installed in a nursery for a test session, in order to achieve an adequate amount of test children to carry out an evaluation of each kind of image output.

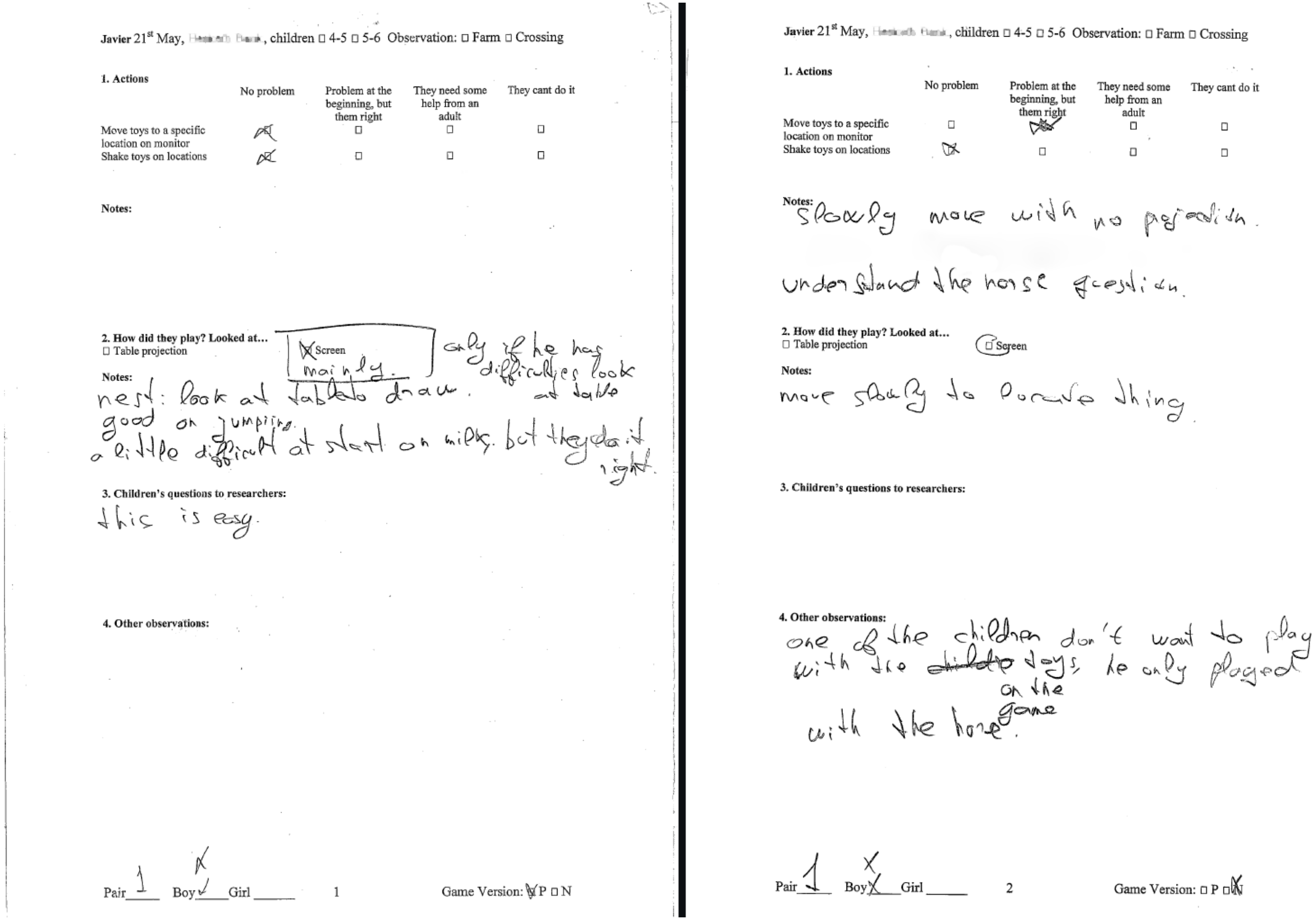
3.3.2.3 Feasibility test session: monitor and surface feedback

Before the test session, a log tool was implemented and installed in the NIKVision computer. This software recorded in files the coordinates of each toy when dragged on the table surface. Each time the Farm game was launched, a new log file was created. This way, a graphic representation of the manipulations of the toys could be reviewed for analysis in lab. This was used to recover usability data of the gestures performed by the children during the game.

During the test session in the nursery, children were grouped in 6 pairs of 3-4 year olds. Each one tested two NIKVision versions: one with both image outputs (monitor and table surface projection) and another with only the monitor output (no projection on the table). Questionnaire papers were prepared for taking notes during the trials while observing children playing. The questions focused on the children's performance of the physical manipulations and their perception of the image outputs. The game version tested was noted at the bottom of the questionnaire paper (see Fig 105). Two adult test assistants wrote independent questionnaires, and later correlated their observation in lab. Questionnaire notes were also correlated with the graphical representation of the log files in order to analyse and compare usability of both versions of the Farm game.

Image projection on the surface was found to have an important impact on children's usability performance. From the log files (see Fig 106), it could be noticed that the movements of toys on the bushes were more precise when image projection was present. When using no projection, toys movements covered a wide area, trying to locate the interactive spot of the bushes. The density of movements on the hotspot was low, and some toys even failed to enter the hotspot area. In contrast, in the projection tests the density of movements on the table surface was high. Children used the icons on the table surface to locate the bushes, and then shake the toys on the spot. Despite this, the observation notes reflected that children spent most of the time looking at the monitor as they preferred to see the 3D farm scenery and the funny graphics and animations. They only looked at the surface image for short periods of time when they needed to locate some interactive object in the farm. Moreover, two couples of children had problems realizing that the icons projected on the table surface were mapped to the 3D bushes on the monitor, and at the beginning they played only looking at the monitor, as if there was no image projection. Only after an adult assistant pointed out to them the meaning of the projected icons did they start to look at them to locate the bush positions.

From the analysis of these observations, it was decided to maintain the 3D scenery on the front monitor, with more funny animations and interactive objects, and to reinforce the presence of image projection with 2D graphics more closely related to the 3D virtual yard. This new iteration was the beginning of the Prototype stage.



Javier 21st May, [redacted], children ☐ 4-5 ☐ 5-6 Observation: ☐ Farm ☐ Crossing

1. Actions

	No problem	Problem at the beginning, but them right	They need some help from an adult	They cant do it
Move toys to a specific location on monitor	☒	☐	☐	☐
Shake toys on locations	☒	☐	☐	☐

Notes:

2. How did they play? Looked at…
☐ Table projection ☒ Screen mainly. only if he has difficulties look at table

Notes:
nest: look at tablet to draw.
good on jumping.
a little difficult at start on milk. but they do it right.

3. Children's questions to researchers:
this is easy.

4. Other observations:

Pair 1 Boy ✓ X Girl ______ 1 Game Version: ☒P ☐N

Javier 21st May, [redacted], children ☐ 4-5 ☐ 5-6 Observation: ☐ Farm ☐ Crossing

1. Actions

	No problem	Problem at the beginning, but them right	They need some help from an adult	They cant do it
Move toys to a specific location on monitor	☐	☒	☐	☐
Shake toys on locations	☒	☐	☐	☐

Notes: slowly move with no precision.
understand the horse question.

2. How did they play? Looked at…
☐ Table projection [✓ ☐ Screen]

Notes:
move slowly to [illegible] thing.

3. Children's questions to researchers:

4. Other observations:
one of the children don't want to play with the ~~childre~~ toys, he only played on the game with the horse.

Pair 1 Boy X X Girl ______ 2 Game Version: ☐ P ☒N

Fig 105: Sample sheet of observation notes for the Feasibility test.

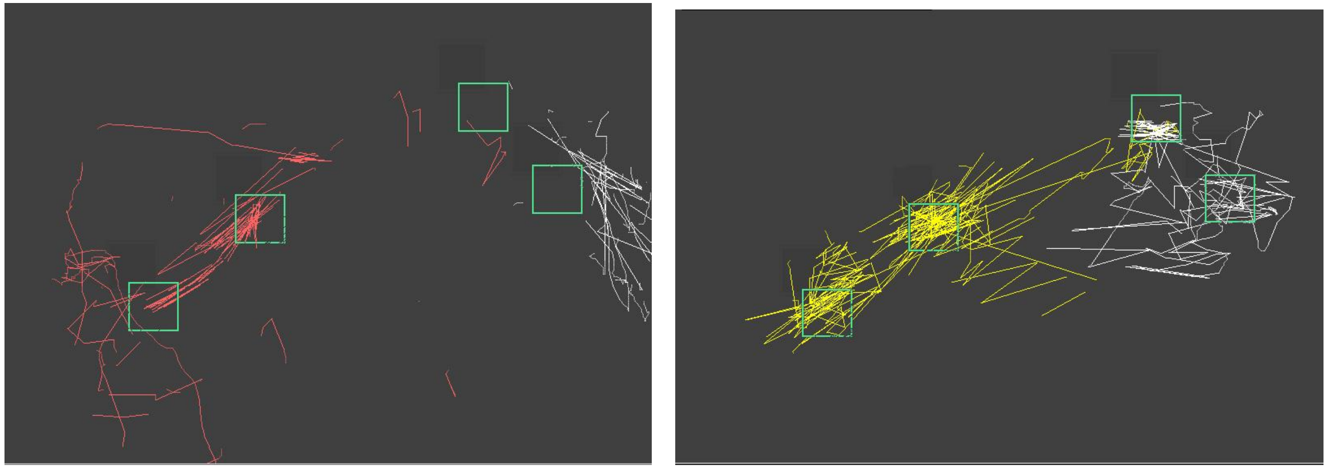


Fig 106: Log data graphically presented as toy paths. Green squares represent the location of interactive bushes in the yard. Left: without projection on the surface. Right: with projection on the surface.

3.3.3 Prototype

As has been explained, the feasibility stage focused mainly on the creation of early concepts of tangible tabletop games which would help to achieve the objectives of this thesis. At the end of the feasibility stage, NIKVision consisted of a tabletop device (see section 3.2) and a simple tangible game (the Farm game). In the next stage, these concepts had to evolve into functional prototypes, capable of being evaluated with children in nurseries and schools. Therefore, Research questions during the Prototype stage focused on factors related to the performance of the User Experience (UX) playing the game; especially regarding fun, physical toy manipulation and group playing.

In order to recover usability and UX data from the "in construction" Farm game, more interactive activities had to be created for the Farm game, and this involved a considerable amount of coding. At this point, it was important to mitigate the risk of spending too much time and effort on developing design decisions which might prove to be unviable in later user evaluations. In order to do that, the test sessions of the game were arranged to quickly detect and retrieve usability and UX issues for each design decision taken during the prototyping process.

The Prototype Stage of the tangible Farm game consisted of three successive iterations (see Fig 107), each one followed by an evaluation session in nurseries and schools, recovery and analysis of data from each session and the subsequent improvements to the Farm game.

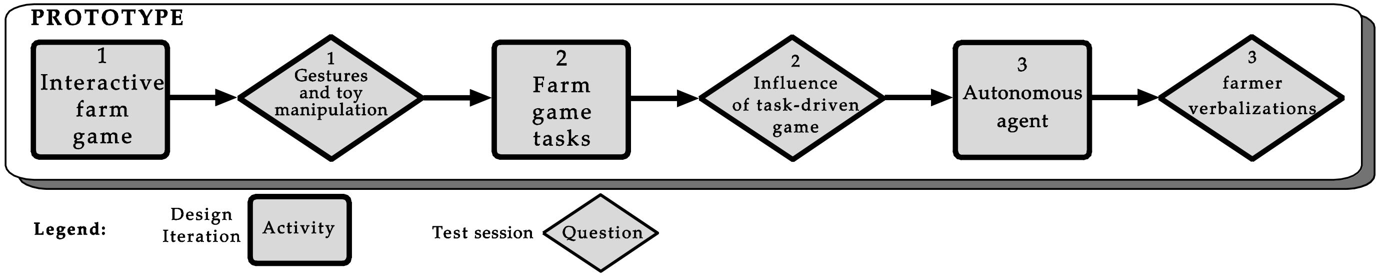


Fig 107: Prototype Stage.

3.3.3.1 *First Prototype iteration: interactive Farm game*

The interactive possibilities of the early concept of the Farm game were expanded with:

- Physical toys: besides the farm animals used in the previous stage, a toy bucket was added. It was augmented with a fiducial on its base, and its corresponding 3D representation on the monitor.
- Interactive virtual elements: New virtual elements were added into the virtual yard: 4 plants, a nest and a barrel; and 3D animations: plants dropping strawberries, eggs appearing in the nest, and wool appearing in the barrel. The 3D bucket was also animated as it was filled with milk. Image projection on the table surface was enhanced to reinforce its meaning with a more detailed 2D view of the yard (see Fig 108).

Fig 108: First Prototype iteration: Farm game prototype with more activities and enhanced 3D (above) and 2D graphics (below).

Each new element added to the game triggered a game event when toys interacted with them. The physical gestures to be carried out with each toy to interact with each element meant a crucial design decision. At this point, the research question was to retrieve the natural and intuitive gestures which children associate between the toys and the virtual interactive objects of the yard. This was the objective of the next test session. Usually in early prototype tests it is common to ask the user to "figure" or "imagine" that some system functionalities are working, but this is not viable with children (Höysniemi, 2004). It is important to remember that children are not really "testing" our prototypes, they are playing, and they will only do so for fun. In situations where an early prototype does not yet have all the functionalities properly coded, a Wizard of Oz method (Höysniemi, 2004) can be helpful to maintain the "illusion" of playing a functional game. This was the method followed in the first prototype session.

3.3.3.2 First Prototype Test Session: Gestures and toy manipulation

This test session took place in a preschool classroom with 4-6 year old children and it was structured using a Wizard of OZ approach. During the trial, an adult assistant was in charge of triggering the feedback and responses of the game according to the manipulations of the children. Animations of the virtual plants, nest, barrel and bucket were activated with keyboard stokes. The children played the Farm game in pairs, and an adult designer asked them to use the hen to lay eggs, the cow to give milk, the sheep to give wool or to look for strawberries in the plants with any animal. No instructions were given about how they had to do each action, as indeed the NIKVision software did not recognize any gesture of the toys on the table. The children's manipulations were observed by the adult Wizard of Oz, who triggered the animations using a keyboard beside the tabletop in the instant some child performed a manifest action with the toy (see Fig 109). In this approach, the children were really receiving feedback from the game which motivated them and encouraged them to continue playing. In this way, they informed of how they wished to perform the gestures while having fun with the game.

Fig 109: First Prototype Test Session: Adult assistant (on the left) observes children playing and triggering game events in the Wizard of Oz version of NIKVision.

The Wizard of Oz approach enabled children to be involved in the design of the physical interactions of the Farm game without being dependent on verbal communication. Indeed, the children informed of how they wanted to use the systems naturally, simulating the physical actions, despite not being conscious of that fact, therefore playing with the game according to their mental image.

Trials were video recorded to be later analised in the lab. From the observation of children performing gestures with the toys, three kinds of gestures were defined as those most commonly used by them to trigger the actions:

- "Jump": many children tried to drop the strawberries, give wool and lay eggs making quick jumps with a toy over the plants, the barrel or the nest.
- "Shake": many children looked for strawberries by quickly dragging a toy in all directions on a plant.
- "Mount": most of the children tried to use the toy bucket with the toy cow just placing the cow over the toy bucket.

It was decided to implement software detection of the "jump" and "shake" gestures. However, the "mount" gesture was discarded because of technical limitations, since the video camera was not able to "see" a toy if it was not placed directly on the table surface. In consequence, the bucket toy was discarded, and the milk activity was redesigned with a virtual bucket in the yard where the children could jump with the cow to give milk.

With the gestures previously implemented, three activities were developed:

1. The hen had to lay eggs.
2. The cow had to give milk
3. The sheep had to give wool

Regarding the wool activity, it was decided to redefine it as some problems had been observed when evaluated in schools. Initially the activity was based on playing with colours: the sheep would give wool in barrels with different colour tints (see Fig 110). Depending on which barrel the children used to place the sheep, the wool was tinted with the colour of this barrel.

Fig 110: First concept for an activity with the sheep.

In the test sessions explained before in this chapter, children performed the toy-jump gesture over the barrels, so the adult Wizard of Oz triggered the animation of the wool, tinting with the barrel colour. However, when they were asked to say what was happening, none of the children were able to explain it. Despite being physically appropriate for children, the activity was not well designed for children's cognitive skills. Therefore, it was clear that the activity should be redesigned.

3.3.3.3 Second Prototype iteration: Farm game tasks

From the results of the previous test session, a script of four interactive activities in the Farm game was drawn up:

1. Collecting strawberries (see Fig 111a): Children have to find hidden strawberries in four plants in the yard. Any animal can be used by being shaken or made to jump into a plant. If it has a strawberry, its animation and sound are triggered, giving feedback that a strawberry has been found. Five strawberries have to be collected to complete the activity.

2. Laying eggs (see Fig 111b): Only the hen toy can trigger this activity. The children have to make the hen jump on the nest, and with each jump one virtual egg appears in the nest until four eggs are laid. Sound reinforces the feedback output of each egg.

3. Giving milk (see Fig 111c): Similar to the eggs activity, the cow has to jump on the virtual bucket. With each jump, the bucket is filled with a little milk. After four jumps, the bucket is filled up.

4. Giving wool (see Fig 111d): due to the problem with this activity described in the previous test session, a new approach was ideated which relied on some activity which young children can easily identify. It consists of a metaphor between the shearing and going to the barber to have a haircut. There is a barber’s chair in the yard. The activity was triggered when children placed the sheep on the chair. Then, the virtual farmer gets some scissors and it is animated as if he were cutting the sheep’s “hair”.

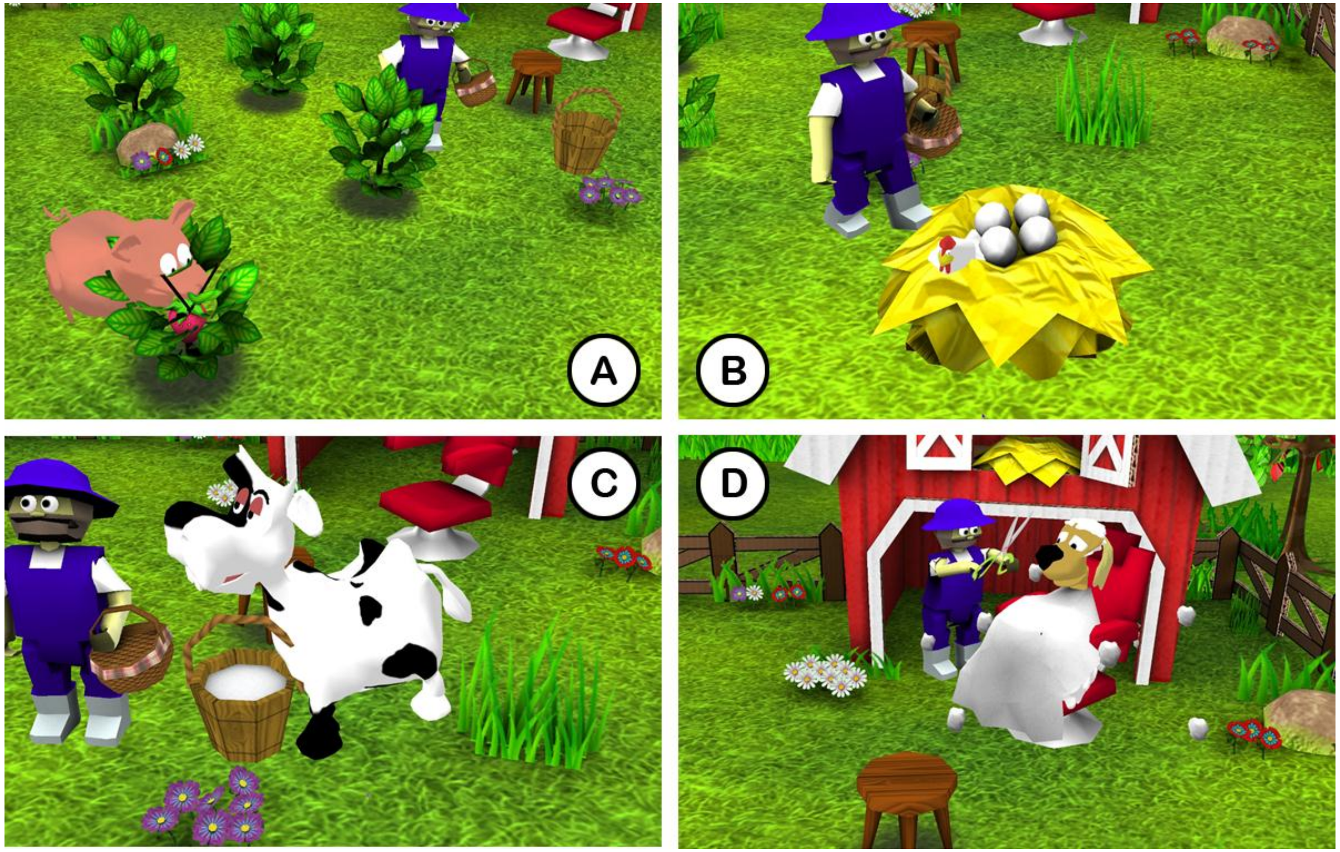


Fig 111: Different activities of the Farm game: A: collecting strawberries. B: laying eggs. C: giving milk. D: giving wool.

As the Farm game was intended to be completely autonomous, needing no adult intervention, it was decided to introduce an autonomous character with the function of guiding the children through the activities. Therefore, a 3D farmer character was modeled, animated and embedded in the 3D farm scenery (see Fig 112). The aim of the virtual farmer is to provide tasks for the children and to ensure that all features of the game are addressed. However, in the context of videogames, Vermeeren et al. (2007) manifested that task driven games may negatively influence users' behaviour and experience, affecting the fun element and also the exploration and discovery benefits of games. The influence of introducing a virtual character as a guide in a task-driven game was the research question of the next test session.

Fig 112: Autonomous farmer integrated in the farm environment.

3.3.3.4 Second Prototype test session: influence of task-driven game

In order to know the differences in the children's experiences when playing with a non task-driven Farm game and with another completely task-oriented one with a virtual farmer, a test session in a school with 4-5 year old children was arranged.

Two game versions were developed:

- Free game: here the farmer agent is silent and does not give any instructions. He only collects the strawberries, eggs, milk and wool that the children produce playing freely. In consequence, children can carry out the activities in any order.

- Task guided game: In this game mode, the farmer takes part in the game giving verbal instructions to carry out the tasks in a fixed order: strawberries, eggs, milk and wool. The level of detail of these instructions was also considered as a research question. Therefore, three different behaviours were modeled to give instructions:

    1. "What to do": the farmer only says what to do to find strawberries, to lay eggs, to give milk and to give wool.

    2. "What and where": the farmer also specifies where the toy has to be put to trigger a specific activity (plants, nest, bucket, barber's chair) with verbal instructions and moving near the object in the virtual scenario.

    3. "What, where, who, and how": the farmer specifies what to do, with what animal, where, and also how to do the manipulation (shake, jump…).

During a full day test session in the school, ten pairs of children tested the game, so each version was tested at least twice. Each couple played with only one game version: free or guided task. If a couple was assigned the "guided task", they only played with one of the three different farmer behaviours. The trials were video recorded, and the log tool was improved to retrieve the instant when each gesture (shake, jump) was recognized by the system (see Fig 113). The system also stored the farmer's movements and verbalizations (see Fig 114). Observation notes were written during each trial so that they could be later matched with the videos and logs, noting down the time when the trial started.

During the analysis of the data collected in the trials, important differences emerged. When children started playing with the free game version they picked one toy randomly and started exploring the yard by dragging the toy on the table surface. As plants took up most of the yard area (see Fig 115) and any toy could shake them, "Strawberries" was always the first activity discovered. The children received feedback by sounds and animations when a toy got into any plant, so they started shaking all the plants randomly. They were not conscious that some plants had strawberries and some not, but occasionally they ended dropping one, and received system feedback on the newly dropped strawberry. Finally, they realized the goal of the game, and started looking for more strawberries. However, they did not try to trigger other activities. Sometimes, if they were handling the cow they accidentally triggered the milk activity, as the bucket area was near the centre of the yard (see Fig 115) and the toys passed by very frequently. Thanks to the animation and sound feedback, the children sometimes realized that there was a new activity in the bucket and explored the bucket with the cow, but not always. The nest and scissors objects were never explored, as they were near the edge of the yard.

Fig 113: Second Prototype test session: Graphic representation of log file. A jump gesture is pointed as a "CLICK" tag.

Fig 114: Second Prototype test session: Verbalizations of the virtual farmer are tagged near the farmer.

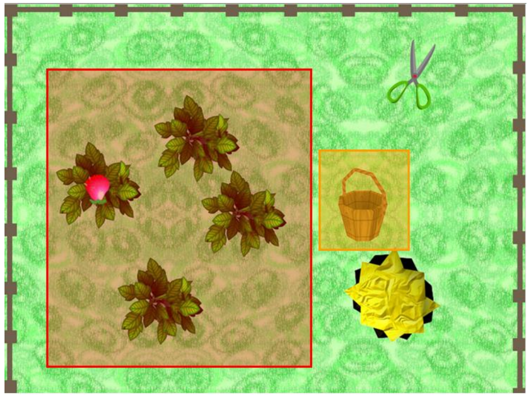


Fig 115: Second Prototype test session: Tabletop activities area coverage.

Regarding the task-guided game, it was observed that all children completed all the activities from beginning to end in the order commanded by the farmer character. The children listened to the farmer's instructions and then tried to achieve only that goal (although the game still enabled them to do all the tasks in any order independently of what the farmer was asking for). On some occasions, children asked for help from adults or friends in some tasks using behaviour 1 (What to do), as they did not know how to complete the task after hearing the instructions. Nevertheless, all the children were able to complete the task with behaviours 2 ("What and where") and 3 ("What, where, who, and how") without intervention. In conclusion, the "What and where" behaviour adds some exploration and challenge to the game without increasing its difficulty, and this was the behaviour finally implemented for the autonomous farmer agent. The "giving wool" task still confused children in all game versions, as children did not perceive it as an activity. The problem was that the "giving wool" did not need any toy gesture to trigger it: the sheep toy had to be kept still on the scissors icon while the barber was cutting its hair. As the children were continuously moving the toy, the farmer animation was interrupted all the time. In consequence, the shearing activity was removed from future game versions.

3.3.3.5 Third Prototype Iteration: Autonomous agent

After deciding how the farmer should ask for the tasks to be performed, the next step was to decide the most suitable expressions and words for the farmer to verbalize. As the research question at this moment was related to verbalization, an evaluation method based on children's verbalization was chosen to be applied in this test: peer-tutoring (see section 2.5.2).

3.3.3.6 Third prototype test session: Farmer verbalizations

A new test session in a school was planned with 4-5 year old children. This time the trial structure was more complex than in the previous tests. A Farm game version without the virtual farmer was developed, in order to give the farmer role to a child. The children were grouped together in threes. They were told that one of them would be the farmer and would have the role of helping the others to play the game. When one of the children agreed to be the farmer, he/she was dressed up in a farmer's hat. This farmer child played with the Farm game alone, so he/she learnt how to play before his/her partners. Then, the other two children entered the test room and started playing under the guidance of the farmer child (see Fig 116).

Fig 116: Third prototype test session: Farmer child is guiding his friends in the Farm game.

The trials were video recorded and later analised in the lab. The value of the information retrieved from this test was very irregular. First, adult intervention was required to help the child-farmer explain and guide the activities because the child had learnt to play with the non-task guided version of the game. This adult intervention probably disrupted the spontaneity of the child explanations to his/her partners. Secondly, 4-5 year old children were still developing their social skills and they felt very shy tutoring other children. The first three trials were frustrating as the farmer children verbalized practically nothing and limited themselves to playing all the game by themselves in front of their partners, so that the latter could see how to play. The fourth child turned out to be a very talkative and extrovert child. He got a lot of fun out of being a farmer and helping and encouraging his partners. He was asked to play the farmer role with the next two groups and he felt happy doing it.

In consequence, the data retrieved after this test session was very limited. It mainly consisted of verbal expressions which the children used to express some gestures of the game; for instance, the fourth child used the word “stomp” to express the toy jump gesture. These expressions were incorporated into the verbalizations of the autonomous farmer agent. This finished the research questions for the prototype stage. With the knowledge gained testing and evolving the prototype, the Farm game entered in its final stage.

3.3.4 Development

In this stage, the work was aimed at achieving a Farm game which could be used as a “Final product”: a tabletop game suitable to be used in nursery and school environments without the intervention of the designer. In previous stages the aim of testing the Farm game with children was formative, as they helped and guided the evolution of the game. But as the game was becoming a final product, the subsequent test sessions were oriented towards assessing whether the game had achieved the objectives of this thesis, using summative evaluation methods. Fig 117 reflects the development of the final game, and the two sessions arranged in a nursery and a school which provided usability data.

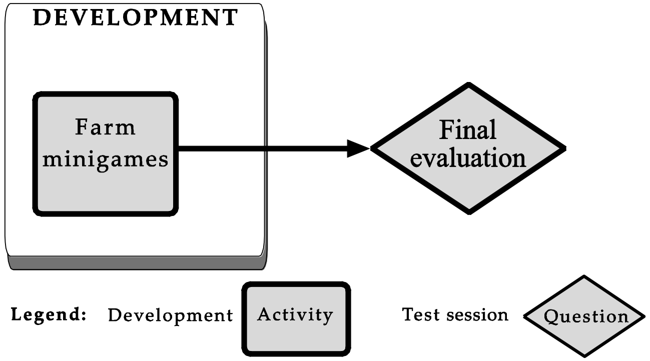


Fig 117: Development stage.

To complete the Farm game as an “expressive” videogame (see section 2.3.3), the set of activities developed during the prototype stage was finally integrated into a script in which the animals take part in the farmer’s son's birthday (see Fig 115). During the birthday, the animals can play three mini-games related to different moments of the party:

1. “Making a cake” mini-game. The farmer asks the animals to help him to make a cake. He asks for 5 strawberries, 4 eggs and a bucket of milk (see Fig 119). When the three tasks are completed, the mini-game ends.

2. “Hide and seek” mini-game. During the birthday party, the farmer’s son asks the animals to hide in the farm while he counts to ten. The farm scene has some places to hide (see Fig 120). The children must hide the animals inside these objects before the farmer’s son counts to ten. Then he starts looking for the animals, trying to find where they are hidden. If an animal is not hidden, or the farmer’s son passes near a hidden animal, he announces that he has found the animal. The mini-game ends when all the animals have been found.

3. “Babies go to sleep” mini-game. At the end of the party, the animals must go to sleep. The pig and sheep have three babies each. They are wandering around the yard (see Fig 121 below), but now it is time to go to bed. The children have to use the pig and sheep toys to “push” the virtual babies to the area where they sleep (see Fig 121 above). The piglets move to keep away from the pig toy, and the lambs keep away from the sheep toy. In this way the children control the movement of the babies to push them to the top of the table surface. When a baby reaches its specific area, the children can see on the monitor how it goes to bed and falls asleep. When all six babies are in bed, the mini-game ends.

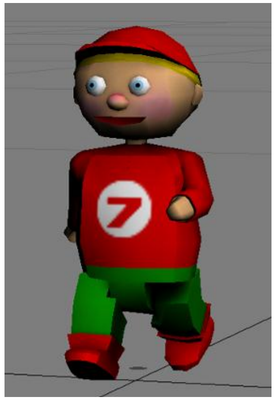


Fig 118: New autonomous agent representing the farmer's son. Farm animals play with him during the birthday party.

Fig 119: “Making a Cake” mini-game. Above: Monitor image. Below: tabletop image.

Fig 120: “Hide & Seek” mini-game. Above: Monitor image. Below: tabletop image.

Fig 121: “Babies go to sleep” mini-game. Above: Monitor image. Below: tabletop image.

3.3.5 Final evaluation

The test sessions at this point focused on collecting extensive usability and User Experience data of the Farm game as a final product. Therefore, the nature of the data collected was summative, and the tools to analyze them were based on statistical methods. These analyses were used to summatively and quantitatively assess how well the final product achieved the objectives fixed for this thesis. However, summative evaluation provides limited help in identifying the breakdowns of the product which are obstructing better User Experience. Considering that the Farm game is actually a research product, it was also interesting to retrieve formative data. Therefore, a combination of summative and formative evaluation methods was planned to provide useful information in order to continue iterating during the final stage of the design process.

Using summative evaluation, adult intervention during test sessions should be minimized. The capture and post analysis of data needs to be a well structured process in order to minimize the “evaluator effect” (Jacobsen et al., 1998): Subjectivity of the evaluator during the analysis of data recovered in the test may be decisive to perceive usability problems. In contrast with a strongly structured analysis process, the trials themselves had no structure as the idea was to collect extensive evaluation data from children who were playing freely with the mini-games. Two test sessions were carried out: a one day session in a nursery (3-4 year old children) and another day session in a school (4-5 year old children). In the nursery, NIKVision was made available simultaneously with the rest of the children's activities, so they could start playing and leaving whenever they wanted with no adult intervention. However, in the school, the tabletop was installed in the library, and the children came from their classrooms to play in little groups of two or three. The broad differences in the structure of the nursery and the school sessions had a notable influence on the results obtained, and have forced to analyze the recovered data separately.

Automatic statistical software was developed to retrieve data from log files recorded during the evaluation session, in order to provide summative statistics about:

- Goal completion (number of complete and incomplete tasks and times a task was replayed)

- Group gaming (number of different toys manipulated per time unit)

- Physical activity (number of manipulations per time unit).

Formative evaluation was provided by videorecording everything that happened during test sessions; not only in relation to game events, but also to the children's emotions and sense of fun, which were considered important data to record. These data was provided by three different video sources:

- Frontal face camera: in the NIKVision tabletop, a video camera was placed just under the monitor to capture a very close and frontal view of children's faces while playing. This view gave information about the emotions which children were experiencing during the game, both positive (fun, motivated, interested) or negative (puzzled, bored, frustrated). It was also important to observe what children were looking at whilst playing: tabletop surface, monitor, partner, adult assistant, or elsewhere. This could be visually noticed during manual analysis of the videos (see Fig 122). As the video camera had a microphone incorporated, the children's verbalizations were also captured and later transcribed into notes.

Fig 122: Different focus of attention, left: tabletop surface; right: monitor.

- Tabletop surroundings camera: a video camera placed in a corner of the test room captured a general view of the tabletop. By placing the camera high up on a tripod, a view of the tabletop surface and the children's manipulations on it were captured. This video stream provided information about usability during the game (problems in carrying out a task, difficulties in performing the physical gestures, etc). Collaboration between children was also retrieved with the camera (to see if the children played independently or helped each other, or if any child stopped playing to watch his/her partner).

- The graphical representation of the log files were later exported as a video file, complementing the live video data recorded during the trials.

Back in the lab, the video streams retrieved in each trial were synchronized in a unique video stream (see Fig 123), giving a complete overview of all game events.

Fig 123: Capturing data during the evaluation: (above) general view of tabletop; (centre) close view of children playing; (below) animated log video streaming.

As stated previously, environmental conditions in the nursery and preschool tests were very different. In the school evaluations, an adult assistant brought children to play with NIKVision in little groups for around ten minutes. Despite letting them play freely, they actually had the feeling of being tested, so the way they played was more rigid than in the nursery where children could enter and leave the game whenever they wanted. The nursery environment was very chaotic and noisy, as the NIKVision tabletop was just one more among all the toys and activities in the room. It was therefore very difficult for the children to hear the voice of the autonomous agent, and they paid little attention to the instructions. For that reason, the results of the evaluation sessions were very different, and this is the reason to show them separately in the following sections.

For each mini-game, the summative data of task completion and physical manipulation is shown. Additionally, measurements of how children played in groups are presented in two graphs showing the evolution of toy manipulation during the trials:

- “Manipulations graph” measures the mean amount of toy movements from the beginning to the end of the games. It gives an idea of how physical activity evolved during the game.

- “Number of toys” graph measures the number of different toys used simultaneously from the beginning to the end of the games. It gives an idea of children’s group playing during the game.

The result of each mini-game is as follows:

"Making a Cake" mini-game:

The measurements focused on three main aspects: efficiency (task completion), task-driven game (provided by autonomous agent), and group playing (small groups of children manipulating toys at the same time) (see table 2).

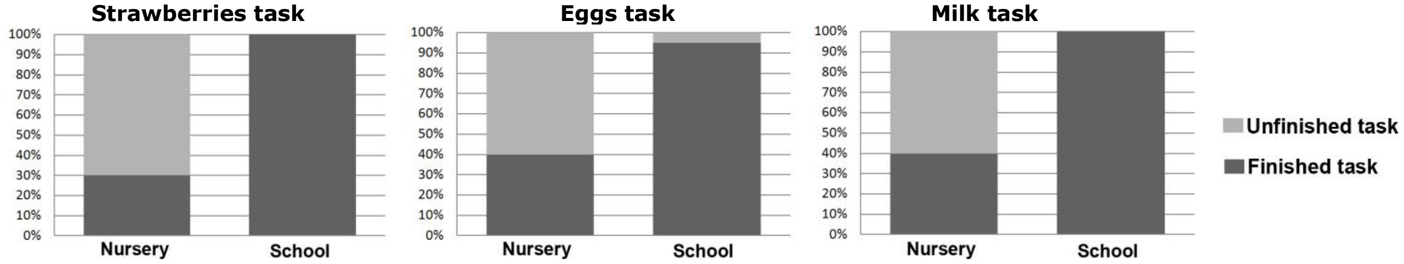
Due to the differences in the test conditions, in the school test nearly all groups finished all the goals of the game, in contrast to the nursery where most of the children did not finish the tasks. Checking with the videorecordings of the nursery shows that carrying out the tasks did not seem too challenging for the toddlers. They were able to shake the bushes, stomp with the cow and hen to give milk and eggs without any difficulty. But their motivation was merely exploration, so they did not worry about the amount of strawberries, eggs, and milk needed to complete the task. The toddlers explored the yard freely, not paying attention to the farmer's verbal instructions. Indeed, the chaotic and noisy atmosphere of the nursery did not help the farmer to be heard. For this reason, the farmer had almost no influence during the nursery test.

On the other hand, the farmer was easily heard in the quiet environment of the school library and the children played mostly following the task order. However, the school measurements show that nearly half the groups that had already finished the eggs and milk tasks liked to continue repeating them as there was no limit on the amount of eggs and milk they could produce.

Table 2: Usability data from the “Making a Cake” minigame.

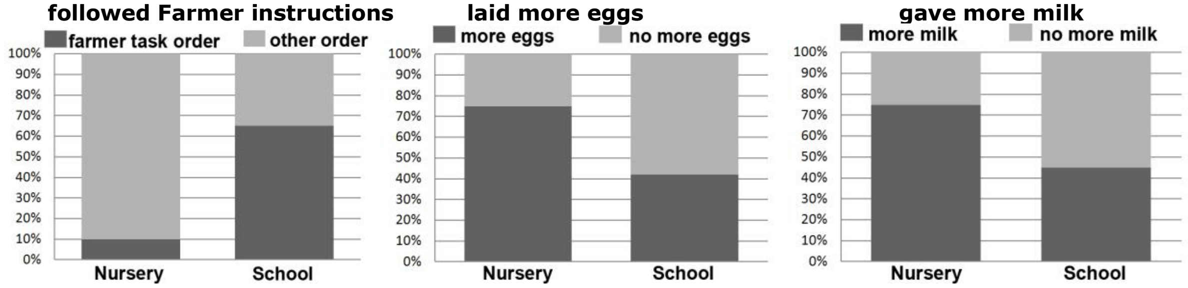
Minigame: “Making a cake” **Nursery: 10 trials** **School: 20 trials**

Task achievement: trials that completed…

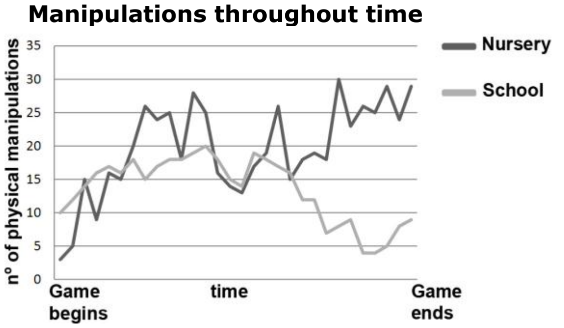


Strawberries task **Eggs task** **Milk task**

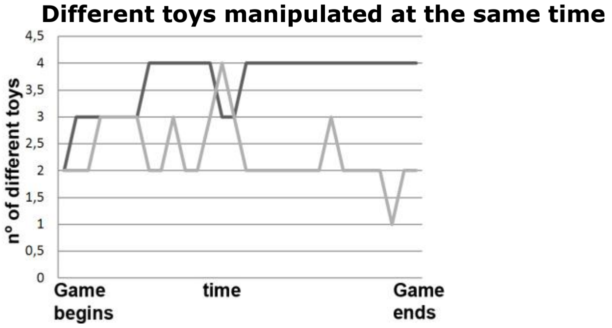
Trials that…



followed Farmer instructions **laid more eggs** **gave more milk**



Manipulations throughout time



Different toys manipulated at the same time

The school trials show more group activity (higher manipulations and more different toys manipulated) during the first half of the game, decreasing at the end of the trial. As the school trial was more task-driven, it shows that the strawberry task (the first task requested by the farmer) allows better group activity than the eggs and milk, which can only be carried out by one toy (hen and cow respectively). This was confirmed by the video streams, where more than one child could be seen trying to find strawberries in the bushes at the beginning of the game, but later only one child carried out the eggs and milk tasks while the other partners looked away. In contrast, the nursery group measurements show nearly inverted results, and the video streams show that, with the toddlers not listening to the farmer's instructions, they were rather shy at the beginning of the game, not knowing how to play. But they soon discovered how to interact with the yard elements, and activity and group gaming increased to a maximum until the end of the game, with up to four toddlers crowding around the table.

In conclusion, when game is not task oriented, physical manipulation and group activity are higher than in the task oriented game. When no instructions are given, children tried in groups to discover all the activities of the farm: A non-task oriented game encourages group playing. Therefore, the farmer's behaviour should focus on helping and supporting children when they get stuck, just bored or frustrated in the game.

"Hide & Seek" mini-game:

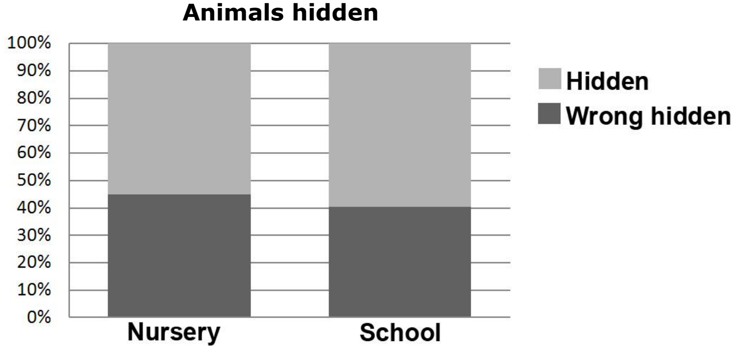
The measurements for the "Hide & Seek" game focused on goal completion and group playing only, as the farmer's son's autonomous agent did not have task-driven behaviour. This could be the reason, in this case, for the nursery and school measurements being very similar (see Table 3).

In both the nursery and school sessions, the "playing in group" graphs show similar evolution over time. The game consisted of two stages with very different interactions. During the first half of the game, the children had to hide the toys inside the virtual objects in the yard. During this part of the game more group activity took place. Activity and group playing then decreased as the farmer's son started looking for animals, so the toys could not move from their hiding places. As the farmer's son found the animals, activity increased near the end of the game. Correlating these measurements with videorecordings, The "Hide & Seek" has an uncommon aspect. Malone (1987) noticed that computer game periods when children have no control and have to wait to regain it have fun problems. However, in this tangible "Hide&Seek" mini-game, when the virtual farmer's son was looking for the hidden animals, the children preferred not to take control of the toys in order to keep them hidden, and they had great fun seeing how the farmer's son was trying to find the animals. This can be seen in their faces and expressions in the videos (see Fig 124).

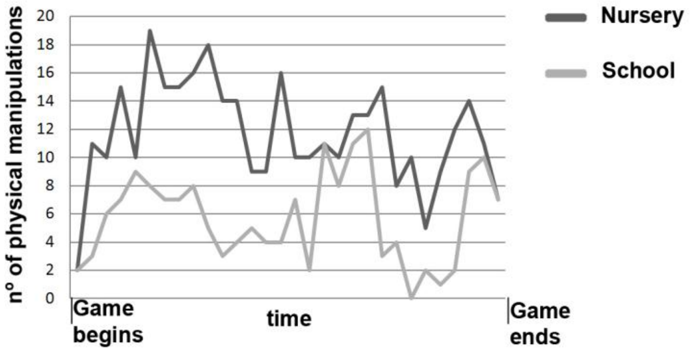
Table 3: Usability data from the “Hide&Seek” minigame

.**Minigame: “Hide&Seek”** **Nursery: 7 trials** **School: 13 trials**

Task achievement:


Animals hidden

Manipulations throughout time



Different toys manipulated at the same time

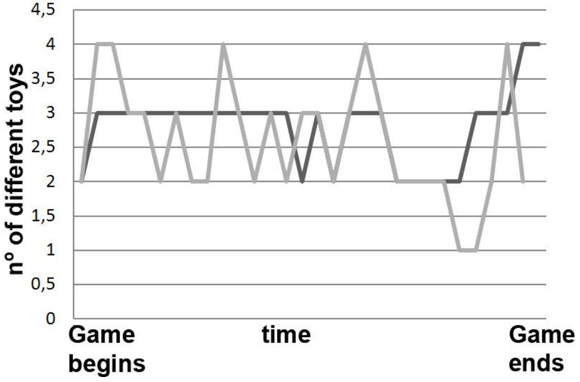


Fig 124: Four year old girls playing Hide & Seek mini-game. Above: seriously hiding toys in the yard. Below: having great fun seeing how the farmer's son was unable to find their toys while keeping their hands away from the toys.

Regarding negative aspects, breakdowns occurred in this game in relation to the task achievement measurements: nearly half of the toys were in fact not hidden when the countdown finished. The problem lay in a "judgment breakdown" (Reason, 1990) as the children judged that a toy was hidden when in fact the system interpreted it as not hidden. Specifically, the system judges that a toy is hidden only if the animal is "inside" an object. But the children had many different interpretations of "hiding". Checking the video streams of the log files, it can be seen that many children judged a toy to be hidden if it was just behind an object from the viewpoint of the autonomous agent (see fig. 90) and others judged a toy to be hidden if it was behind an object from their own viewpoint.

Fig 125: "Hide&Seek" minigame: Cow and pig are hidden behind a bush in relation to the autonomous agent.

Such differences in what children understand by "hidden" should be taken into consideration in future improvements of this game. Future designs of virtual objects where animals can hide should give visual clues of how to use them to hide animals; e.g., the children had no problem in hiding inside the barn because it is clear how to do this.

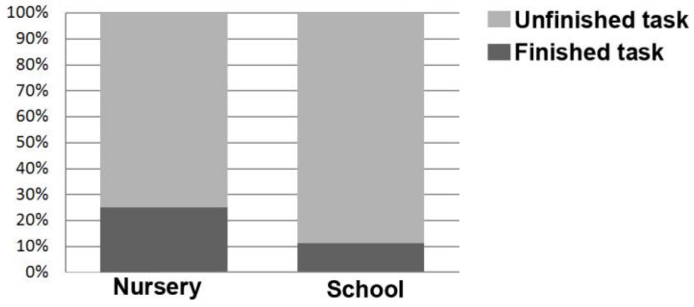
"Babies go to sleep" minigame:

Similar to the previous game, measurements of the "Babies go to sleep" mini-game focused on game completion and group activity, as can be seen in Table 4.

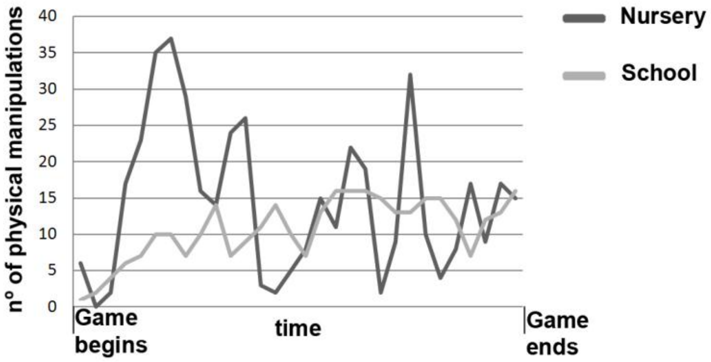
Table 4: Usability data from the “Babies go to sleep” Minigame

Minigame: “Babies go to sleep” **Nursery: 4 trials** **School: 9 trials**

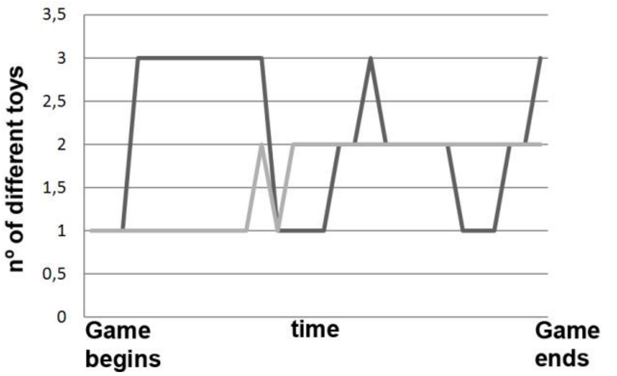
Task achievement: Trials that finished the minigame



Manipulations during time



Different toys manipulated at the same time



The “Babies go to sleep” design relied more on tabletop interaction than the other mini-games. In the “Making a cake” and “Hide & Seek” mini-games, children’s attention focused most of the time on the 3D farm environment shown on the monitor and only occasionally on the table surface to locate interactive zones. But in the “Babies go to sleep” mini-game, their attention went nearly all the time to the table surface, where the babies ran randomly trying to avoid going to bed. The task completion measurement shows that the game was much too challenging for the children. Both in the school and nursery, only one group succeeded in finishing the game. The children showed frustration with this game as the control of the virtual babies required very slow and precise movements of the toys and the children movements were too rough for the precision required.

Regarding group activity, as only the pig and sheep can interact with the babies, measurements show worse activity than the other games as only two children can play at the same time.

Taking all this into consideration, it is clear that this mini-game should be redesigned to adapt it to the psychomotor development of toddlers. Also, group playing would improve if all the toys could be used to “push” the babies. This way, children may cooperate in pushing a baby in the right direction and blocking its movements with more than two toys.

Final conclusions of the games design process will be given in section 3.5.

3.4 Exploring new games for physical collaborative play

3.4.1 Introduction

The classification for digital manipulatives proposed in section 2.4.2 has been the base for the creation of a new set of “exploratory” games that aim to promote collaboration between children. Innovative tabletop toys have been also created to control these games, using the outlined three different approaches: “token”, “name” and “token-constrained”. These toys have been designed to be used as “readiness-at-hand” manipulatives. The direct approach has been taken into account to achieve easy understanding of the physical affordances of toys, so that children would intuitively use the toys and their interaction focuses on exploring the “rules” of the tabletop games. However, as new interactions were needed to be recognized, limitations on using the Reactivision framework appeared. Consequently, new functionalities were added to Reactivision in order to detect all the new manipulations required to support all the interactions associated with the new toys created. The specific details of the implementation of the new functionalities of Reactivision are set out in Annex 2.

The following games were set out for one day in the CosmoCaixa Museum of Barcelona During IDC’2010 International Conference. Observation of children playing freely with the games gives some insight into the usability and children's collaboration of the games.

3.4.2 Math game

Traditionally, physical tokens are used for first steps in Math with children in Montessori education. Manipulation of identical discrete pieces of wood or plastic helps young children to solve their first arithmetic problems. This approach is used in NIKVision tabletop with a Math computer game where children have to use little plastic tokens to complete simple arithmetical operations suggested by the computer. The active surface shows an incomplete operation: the unknown factor may be the result, as well as any operand. Children can place physical tokens to complete it (see Fig 126). All tokens represent an arithmetical unit; spatial rules give tokens a function depending on the area of the operation where they are placed.

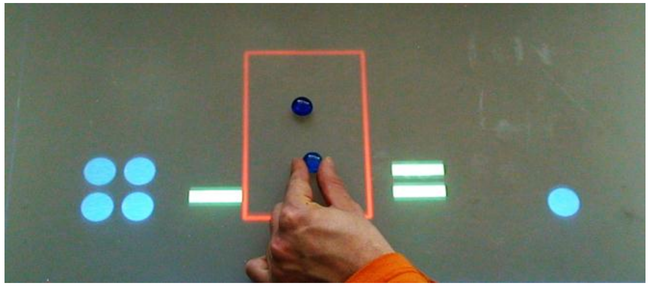


Fig 126: NIKVision calculator game using plastic tokens.

In the first version of the Math game, the table showed only the incomplete operation, without giving any graphic clue of where children must place the tokens. In fact, children could place the tokens in any part of the arithmetical operation. If the operation built with the token is right, the computer sends positive feedback and proposes a new incomplete operation. However, during early tests of this game with a couple of children in the lab, they did not understand the game and asked where they had to place the tokens. Their first reaction was to place the token just on the graphic blue circles. This action gave the clue that naturally, in token games, graphical representations on the table surface are interpreted by users as areas to place the physical tokens. In the next version, a red square indicated the area of the incomplete operand or the result of the operation. In the museum test, children understood that they must place the tokens inside the red area and build a correct arithmetical operation. They could still place tokens outside the red area, but no one did that.

3.4.3 Drum sequencer game

Music learning can also benefit from this token approach. Music scores can be interpreted as a spatial configuration of notes (tokens) over a bi-dimensional surface in which horizontal axis represents time, and vertical axis defines a sound property. Based on paper drum scores, a music sequencer application was developed for NIKVision. Children create their own drum beats distributing plastic pieces over a graphic score shown on the surface (see Fig 129). Each coloured row represents a different drum instrument. Beat is reproduced from left to right. Children can explore the relation between the spatial distribution of tokens and the sound beat in groups, collaborating and sharing their opinion with the other participants. This game is intended to be used by teachers to explain music rhythm concepts in a creative and collaborative way.

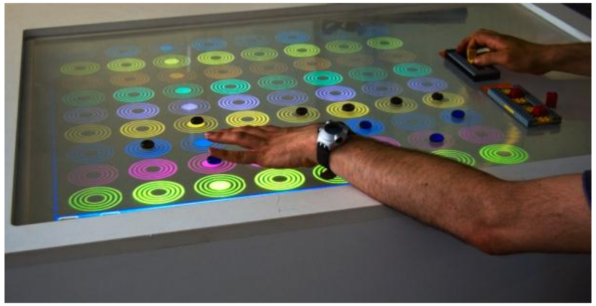


Fig 127: Drum sequencer game.

Also, a pair of token-constrained toys has been designed to control some attributes of the game:

- “Beat Store”: This is an associative toy which consists of a plastic rectangle with four holes within a plastic token which can be inserted and removed. It is therefore an associative toy where each hole has a meaning in the application. When the user has finished a drum beat, he/she can place the “beat store” anywhere on the table, and insert a token in one hole, meaning that this beat is “stored” in that hole (see Fig 128 above). This way, up to four different beats can be stored in the toy. These beats are reproduced when a token is present in their associated hole, mixing with the physically defined beat on the table. By combining up to four tokens in the “beat store” toy, the user can quickly activate and deactivate beats in a creative way.

- “Speed fader”: This consists of a plastic rectangle with a token restricted to move only along its vertical axis (see Fig 128 below). In the “drum sequencer” game the “toy audio fader” is used to control the speed of the beat. At any point in the game, the fader can be placed anywhere on the table, and the token displaced to regulate the speed of the music. Then, the user can remove the toy from the table, maintaining the established speed, and continue composing beats with the tokens.

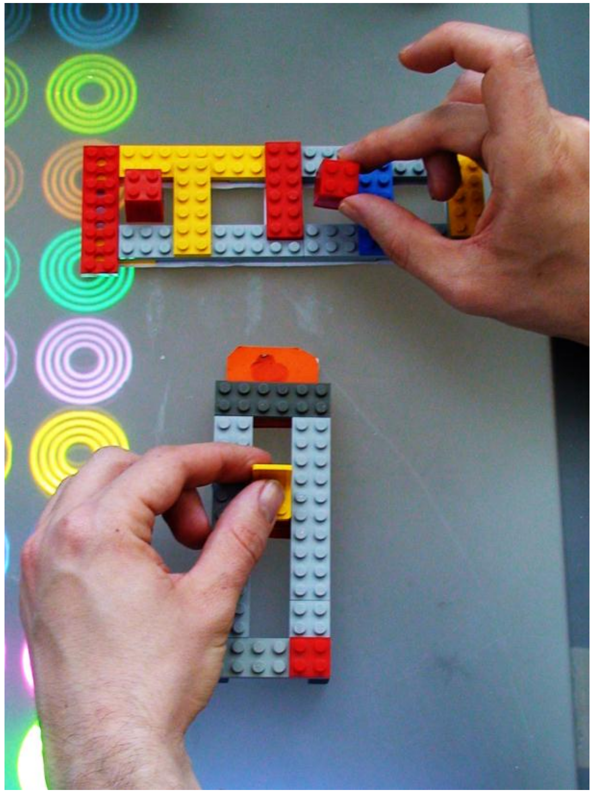


Fig 128: Above: Associative beat store. Below: manipulative audio fader.

During the test in the museum, the "Drum sequencer" engages the children to play in big groups, crowding around the table (see Fig 129). The large amount of stones at the disposal of children meant that any child was able to play the game. Children shared their opinions about the beat, verbalizing and suggesting changes, whilst placing, moving and removing the stones. Although children were not really cooperating to create music together, many interactions between children emerged while they were manipulating the tokens in this game.

Fig 129: Drum sequencer game tested by a group of 9 year-old children

3.4.4 Draw game

Children often build their own toys for their games, drawing and cutting them out. This inspired the "Drawing" game for NIKVision, in which children could create their own manipulatives and introduce them in the tabletop application. In order to do this, conventional papers were promoted to digital manipulatives by printing a fiducial on the corner of the paper, thus giving it a "name" in the system. A child can draw anything on the paper (see Fig 130), and the system recognizes when the paper is present on the table surface, "capturing" the drawing and digitizing it as a computer manipulative which children can move using their hands. An example of a game using this concept: there is a graphic virtual environment on the table surface with some virtual caterpillars crawling (see Fig 131-1). A voice explains to the children that the caterpillars want to change to butterflies, so they have to draw the butterflies on a piece of paper. Children are provided with the "named" paper where they can draw a butterfly in the centre. Each time a child places a piece of paper with a drawing of a butterfly (or anything else!) on the tabletop surface (see Fig 131-2), the system detects the fiducials and retrieves its position and orientation. In this way the drawing is captured as a digital bitmap and copied to the surface. When the child removes the paper, the caterpillar changes into the butterfly which he/she drew and then flies away (see Fig 131-3). Children can interact with the computer manipulatives of the drawings using their hands, hitting and dragging them on the table surface.

Fig 130: "named" paper with drawing.

During the test, the game did not seem to promote collaboration between children, but it was curious to see how children were really engaged in drawing and passing the paper to the computer, interacting only with their own digital drawings and ignoring the drawings of other children.

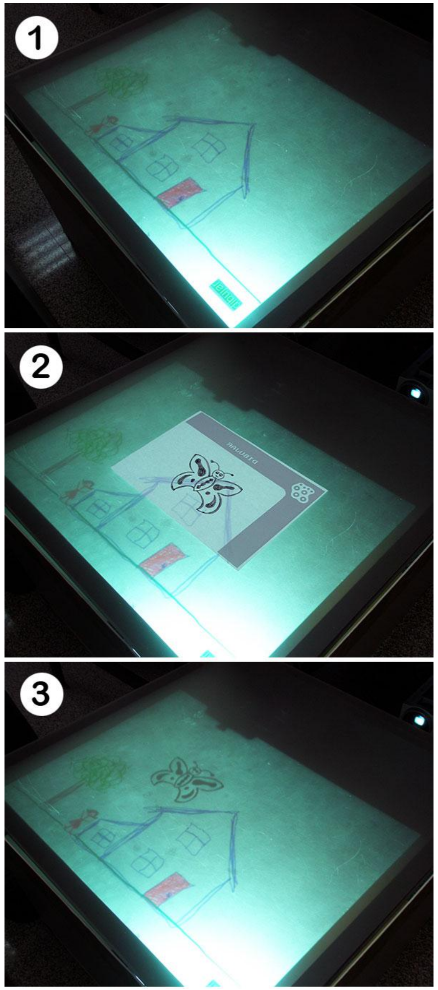


Fig 131: “Draw your story” game. 1: Graphics and voice expose a new situation. 2: Children draw on a piece of paper and place it on the table. 3: The drawing is “captured” as a virtual representation.

3.4.5 “Asteroids” game

Many toys have mechanical structures which add new interactions: e.g. a spaceship toy may have a button that, when pressed, simulates that the ship is firing using sound and light. Taking this concept, a spaceship toy was designed and built to be used in NIKVision tabletop. It has a button on the top which mechanically makes a visual token appear when pressed (associative token constrained) and disappear when depressed (see Fig 132). The meaning of this action is that the spaceship toy launches a virtual missile when the token appears.

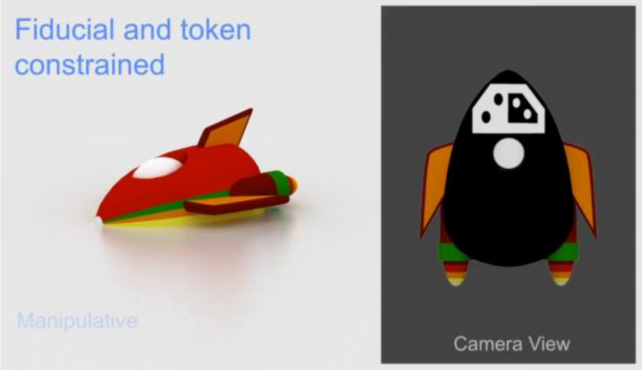


Fig 132: Left: Spaceship toys with mechanically triggered button on top. Right: toy ship seen from below the table.

The spaceship toys have been used in a tabletop adaptation of the classic Atari™ videogame “Asteroids”. Two children should collaborate to destroy all the virtual asteroids which appear on the active surface using the physical toys. Each time they press their spaceship toy, a missile launches which may fragment an asteroid when impacted (See Fig 133).

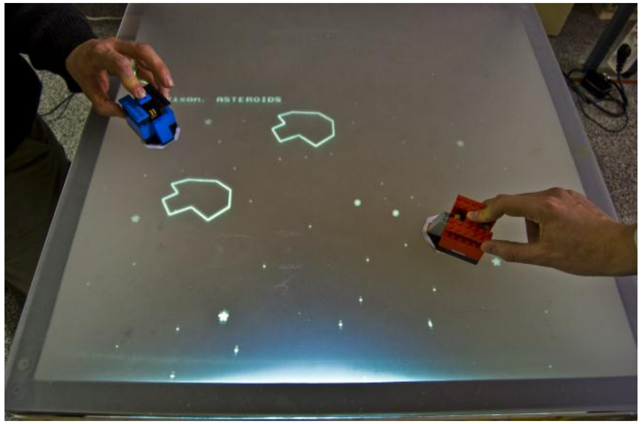


Fig 133: Asteroids game with physical spaceship toys.

The nature of the Asteroids game is purely cooperative, as players share the same objective: to clear the screen of asteroids. However, during the trials in the museum, children usually played independently, using their own ship to clear only the asteroids near their area on the tabletop. Even so, the game does indeed promote collaboration as children verbalized a lot while playing in pairs, as one child was continuously asking the other player for help when an asteroid escaped from his/her own area to the other player's area.

3.4.6 "Pirates" game

A fan interactive toy was built. It has a mechanical rotational constraint which makes a token appear and disappear (associative token constrained) when the child rotates the blade of the fan (see Fig 134). This way, the tabletop device interprets that the fan is spinning when the constrained token is detected, and the system counts how many times per second the token appears and disappears, deducing how quickly the fan is spinning. With this data, the game simulates that the fan is virtually generating wind which has an effect on virtual objects.

The performance of the fan toy is shown in the "Pirates" game, in which children must use the fan to generate virtual wind in order to move a virtual pirate ship. In the initial version, the game had two fan toys, so two children could collaborate in driving the ship to a treasure island (see Fig 135). However, when tested with a couple of children in the lab, although they tried to collaborate using the fans, they actually obstructed each other by spinning the fan in different directions. Finally, the game was redesigned to give different roles to each child. In the new "Pirates" version, one child (the sailor) is in charge of the fan, driving the pirate ship across a virtual sea, looking for treasure ships. This "sailor" has to drive the pirate ship using the fan toy, closing in on a treasure ship. The other child is in charge of the cannons, using a token toy to aim and fire the cannons at the treasure ship, until it sinks and leaves the treasure (see Fig 136). Giving different roles to the children promotes a high level of collaboration in the "Pirates" game. During the test, the children showed their motivation with continuous verbalizations between each other in order to coordinate their actions in the game.

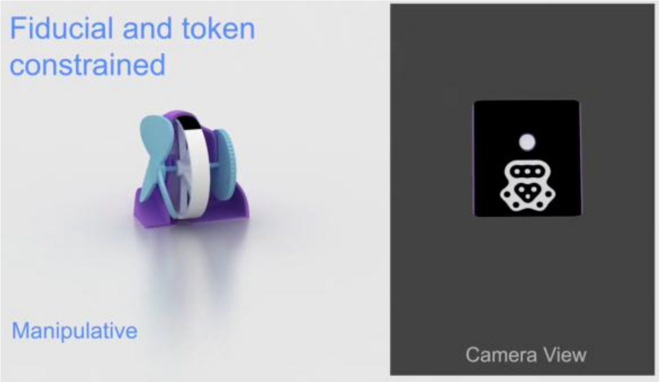


Fig 134: Left: fan toy. Right: toy seen from below the table.

Fig 135: Two fan toys collaborating (but really obstructing each other) to move a pirate ship.

Fig 136: Children collaborating in the Pirates game to sink ships.

3.4.7 Observed collaborative behaviours

This set of games was successfully shown in on day session in the CosmoCaixa Museum of Barcelona. Different collaborative behaviours where observed in each game:

- In the Drum sequencer game, children create drum beats by placing stones in a virtual music score. Children have equalitarian roles in the game. There are a lot of stones at their disposal, so no child could monopolize the game. Children share their compositions with other children and can change the compositions at any moment, in a very collaborative way. Children explore the rules of the beat composition by placing, moving and removing the stones on the table.

- In the “Drawing” game, children share their drawings with other children by translating the content of physical paper to the virtual space of the table. As a lot of paper is at the disposal of children, they do not monopolize the table while they draw, so all children have equalitarian roles. Then, all drawings are at the disposal of being virtually manipulated by any child.

- In the “Asteroids” game, each child is provided with a spaceship toy with an identical role: to shoot asteroids. There is no competitive element in the game. Collaboration between children is manifested in the distribution of table areas. One child focuses on one side of the table and the other on the opposite side. When an asteroid leaves one child's area, he/she encourages the other child to shoot the escaping asteroid.

- In the “Pirates” game, two different roles are used. One child controls the movement of the pirate ship, and the other aims the guns. No child can take both roles by him/herself, thus roles are dependent. Children collaborate in hunting and sinking other ships, verbalizing all the time to encourage the other to carry out some action relating to his/her role.

The kind of digital manipulatives used in each tangible game has an important influence on the physical interactions associated with them and how this affects children collaboration:

- **“Token” toys**: These toys stabilize space relationships with areas of the table surface, acting on game properties. Thus, token toys are based on “verb” metaphors. In the “Math” game, they add a unit to the operand where they are placed, and in the “Drum Sequencer” game, each token activates a sound. Interaction with token based games occurs by distributing tokens in different areas of the table. The active image on the table surface must give clear visual clues of areas associated with the tokens. Collaboration in these games is ensured as children do not monopolize the toys, since the games usually have many identical token toys at the disposal of children.

- **“Name” toys**: Toys have individualized identifications in the system; thus, each toy has a different role in the tabletop game. Interaction begins when the toy is placed on the surface. Spatial relationships established between areas of the table and toys, but different identified toys have different game rules. Collaboration in the games is based on each toy's role. If a task in the game is made by a single role, a child might monopolize the toy, while the others are kept waiting for the toy to become available. Designing role dependences (a game task is made by using more than one role at the same time) may promote children's collaboration. A very special example of a “named” toy is the paper in the “Drawing” game. The paper uses a “name” metaphor: its mere presence has an effect on the game. But the effect of the paper is based on the “attribute” metaphor: The drawing (texture) of the paper defines the interaction.

- **“Token-constrained” toys**: These toys use the “verb” metaphor. In the “Pirates” game, the presence of the fan toy on the table has no meaning in the game (absence of “name” metaphor), but spinning the wheel has an action on the game (pushing along the virtual pirate ship). However, token-constrained toys can also use a “name” metaphor; e.g., the spaceship in the asteroids game (its presence has meaning in the game: it is the player's spaceship, different from the partner's one, and might be destroyed by virtual asteroids), and pressing the button (token-constrained) acts (“verb”) over virtual elements (destroys asteroids). Interaction with token-constrained toys combines the “name” and “verb” duality. With the “name” metaphor, its mere presence has meaning in the game, and can establish spatial relationships with other elements. Therefore, children collaboration is based on the role of the “name” toy: Each child takes the role of the toy he/she is manipulating. With the “verb” metaphor, the user manipulates the tokens of the toy to change attributes of the game. In this case, collaboration may be promoted by giving a child the role of manipulating the toy, and other child manipulating the constrained token.

3.5 Conclusions

During the research of this thesis, NIKVision tabletop and games have evolved from a mere roughly implemented concept to a finished product.

On one hand, NIKVision tabletop device started off from a very simple concept to research the feasibility of using conventional toys as controls in videogames for pre-schoolers, and finally it became a complete tabletop device ready to be set up and used in nurseries and schools.

All the materials and components used in the device are common technology, so the tabletop can be easily replicated at relatively low cost.

During the tabletop design process, keeping the surface low enough to be adequate for young children has been achieved by an optimal design distribution of optical components (camera and projector) supported by reflection in a mirror inside the table.

NIKVision tabletop differs from other similar devices due to the addition of a conventional vertical monitor for 3D image output, as well as table surface active imaging. During evaluation, observations proved that the image monitor helped to reinforce children's engagement and sense of fun.

NIKVision games combine computer activities with conventional toddler’s toys, reinforcing physical manipulation and group activities with computer augmentation. In this way, new interactive experiences emerge with the benefits of both physical manipulatives and computer manipulatives.

A user-centered design lifecycle has been used during the creation of a tangible Farm game. The iterative nature of this process has helped not only to locate and fix breakdowns in the performance of the tabletop and games, but also to guide their evolution from very early concepts to final autonomous products ready to be used in schools and nurseries. The involvement of children has been achieved with frequent test sessions in nurseries and schools. These sessions were based on the observation of children having fun with the tabletop game. The notes, videos and automatic log files were recovered for analysis in the lab in order to guide subsequent design iterations.

Usability results from the evaluations show that children are able to play in little groups with the NIKVision tabletop and have no major problems in carrying out all the mini-games while having fun. Formative evaluation suggests improvements in the degree of challenge of some mini-games, and the reinforcement of the physical manipulations of the game to motivate children towards group playing.

New possibilities of physical manipulation of toys in tabletop games have been explored with the creation of a set of toys based on the new classification of digital manipulatives proposed in section 2.4.2. With the games designed for these toys, the collaborative behaviours of children have been observed, and relationships between the kind of digital manipulative (“token”, “name” or “token-constrained”) and children collaboration have been found.

From the experience gained through the lifecycle of NIKVision, several lessons can be extracted which may be useful for future projects on tabletop technologies for pre-schoolers:

- The addition of a conventional vertical monitor, to complement the active image shown on the table surface, has important benefits. It becomes an important reinforcement of fun during the game, receiving most of the attention of the children playing; active image projection for its part provides help in locating interactive areas in the virtual game area.

- Even though the tabletop device is optimally designed to support more than one children playing at the same time, collaboration will only emerge if the toys and games are optimally designed to promote this behaviour:

    - Games which use an **expressive approach** (i.e. have a history of interaction and are oriented towards achieving one or more tasks) encourage children to take roles when playing the game, by: (a) one child commanding the story flow by manipulating the toys, while the others observe or give verbal suggestions; or (b) all children playing actively using one toy each but performing different tasks, so they do not actually collaborate.
      In these situations, giving different and interdependent roles to each child with dependences between each other (one child cannot finish a subtask without the help of another) forces children to collaborate in achieving the game goal. Children acquire roles in a tangible game through the particular toy they are manipulating. The functions associated with the toys define the roles, and the collaboration needed to play the game.

    - Games using **exploratory approaches** (i.e. children discover the rules of the games by playing, and this exploration is the only task of the game) encourage children to explore, discover and learn by "trial and error". Children get equalitarian roles in these kinds of games, observing and using what other children are discovering while exploring the game. Collaborative behaviours rely on the sharing of the learning and creations obtained during gaming.

- Physical exploration and co-discovery should be the most important factors to be considered to promote more collaborative activities in a tabletop game. Expressive task-driven games bring more rigid interaction, to the detriment of co-discovery and fun. Rigid task-driven guidance should only be used for evaluation purposes as it helps children to test all the tasks and subtasks which the game is composed of. The final version should be mainly based on free play, and autonomous agents should be used only to engage, help or transmit pedagogical content.

- Guidelines extracted from previous literature on videogames and children may be useful, but designers must consider new ways of TUI interaction which are closer to physical gaming. The incorporation of new ideas to encourage children's cooperation and social interaction when manipulating toys should be the main motivation during the ideation of new games, and the main usability measure during the evaluation of the game.

- Regarding testing, the most important thing to consider is that children are using the products just for fun. The structure of the test sessions should therefore rely on observing the children playing freely with the new product.

  Nurseries and schools are very versatile environments for developing constructivist projects involving adult designers and children. Toddlers have difficulties in adapting to new environments and new people. Therefore, children may have unpredictable reactions in laboratory test sessions, added to which it is difficult to arrange frequent visits to the lab and usually only small groups of children can enter the lab at a time. On the other hand, many teachers are willing to collaborate with researchers offering their classrooms and time, provided of course that all ethical questions about testing with children have been carefully considered and permissions from parents have been granted. For designers, classrooms provide a sufficient number of users for formative and summative product evaluation, as well as being a favourable environment for inspiration and creativity.

4 Conclusions and Future Work

4.1 Conclusions

The objectives planned for this thesis and outlined in section 1.2 have been successfully accomplished in the terms described below:

- The current state of Tangible User Interfaces (TUI), active surface technologies and Children-Centered-Design methods have been exhaustively analysed. The results of this research have been used to:
    - propose an innovative methodology to analise, compare and measure the tangibility of any TUI. Based on this methodology, a new classification of digital manipulatives for tabletop devices has been proposed to cover all types of tangible controllers on active surfaces.
    - define the methodology to be used to design a tabletop prototype involving the children throughout the whole design lifecycle. The methodology allows to recover valuable usability and Children Experience data from frequent test sessions in nurseries to be used to guide the design lifecycle of the NIKVision system.
    - acquire the knowledge needed to afford the design of a tangible tabletop device especially adapted to preschool environments.
- A prototype (named NIKVision) has been created, which supports natural interaction with preschool children, provided by the manipulation of physical objects. NIKVision system includes:
    - A tabletop device, the main characteristics of which can be briefed in the following points:
        - Interaction with the table involves physical manipulation of objects on the table surface
        - Users receive image feedback from two graphic outputs: 3D environment on a conventional monitor on a side of the table, and 2D environment on the table surface, where interaction takes place.

        - Its dimensions comfortably support up to five children playing at the same time, either standing or kneeling.

        - It can be easily replicated and produced by other researchers or designers using simple and non-expensive technology.

    - A set of games and corresponding toys:

        - Attractive and intuitive to children.

        - Without electronics or any other kind of technology to make them fragile. Therefore, they are endurable under extreme use by children. As they are computer augmented only with fiducial printed markers, any conventional toy can be easily expanded to be used in the tabletop with nearly no effort and cost.

        - That reinforce group and collaborative behaviours in children.

In the final evaluation, the NIKVision system has proven to be attractive and fun for children, reinforcing physical gaming and supporting small groups of children playing at the same time. Therefore, it can be asserted that the main objective of this thesis, to bring computer technologies based on TUI to preschool educative environments, has been successfully achieved.

The knowledge and experience acquired in this work may be useful to future developers of tangible tabletop games for young children, who were looking for physical, social and cooperative computer gaming.

4.2 Contributions

The main contributions in this thesis can be summarized in the following points:

- A new methodology to analyse, compare and measure the tangibility of physical objects used in TUI applications. It is based on two concepts: embodiment and metaphor, which are analysed from a direct design approach. Considering this methodology, a general classification for digital manipulatives on tabletop applications has been proposed. Any physical control in a tangible tabletop application can be classified as a "token", "named" or "token-constrained" manipulative. This contribution has been published in Marco et al. (2010c), Marco et al. (2010d) and Marco et al. (2011).

- NIKVision system is the first in successfully combining tabletop technologies with tangible interaction with toys, applied to preschool environments. The ideas proposed for using conventional toys on a horizontal active surface can be used in another similar tabletop system, not only in the prototype described here but also implemented in different tabletop devices (commercial or not). NIKVision is a non-expensive and easily replicated tabletop device. NIKVision system has been described in different publications (Marco et al. 2007) (Marco et al., 2008a), (Marco et al. 2008b), (Marco et al. 2009c).

- This dissertation narrates a complete design lifecycle in which many Children-Centered-Design methods were adapted and used. It can therefore be used as a practical case study for tabletop game designers who are thinking of developing new tangible applications for young children. This contribution has been published in Marco et al. (2009a), Marco et al. (2009b), Marco et al. (2010a), Marco et al. (2010b), Marco et al. (2010d).

4.3 Future work

There are two main lines of future work for NIKVision, and in both of them the author is already involved:

4.3.1 Exploring children collaboration supported by digital manipulatives

NIKVision tabletop has proven its potential to support collocated gaming in small groups of children. The toys and games outlined in section 3.4 are only the beginning of more extensive research into children's collaborative behaviors. New toys and games will be created in order to explore new techniques in tangible interaction to reinforce collaboration in preschool children.

In this context, computer augmentation in toys should be expanded to fully support Ishii’s original TUI definition of Tangible Bit: “control and representation of digital content”. All toys designed in the work carried out in this thesis have only the control function. Therefore, a clear future line of research for NIKVision is to design new toys which will combine the control and representation functions, reaching full embodiment. And this will be achieved not only by displaying digital information on the toys, but furthermore enabling the system to control the toys itself by moving them autonomously and being able to change their state.

Once more, children's involvement will be a main requisite during the design of the new toys and games. Therefore, new case studies of the practical application of innovative CCD techniques will surely emerge from this future work.

4.3.2 Children with cognitive disabilities

In the same way NIKVision has succeeded in bringing collocated computer gaming to nurseries, this technology should also be helpful in the social development of children with cognitive disabilities. Obviously, children with some kind of cognitive disability show significant differences between each other in terms of capabilities, motivations and social relations, but they all have in common that their disabilities have consequences for their learning and maturing process.

As outlined in section 2.2, tabletop spatial configuration helps to reinforce collocated and face-to-face interaction between learners, and thus it seems an ideal configuration to help these kinds of children. There has been some previous research into applications of tabletop technologies with children with Asperger’s Syndrome (Piper et al. 2006).

The GIGA group has experience in developing applications for children with cognitive disabilities, provided by the collaboration with Alborada School for children with special disabilities in Zaragoza (Spain). Collaboration with Alborada staff to develop new games and toys for NIKVision tabletop has already begun. Interaction with the tabletop is going to be expanded with special devices designed for children with disabilities, like communicators.

It will be needed to research new methods of involvement and evaluation of tabletop games for children with cognitive disabilities. From this new research work, an extensive and useful experience of applying TUI and CCD technologies to children with special needs could be obtained.

Annex 1: NIKVision tabletop design

The design of a tangible tabletop suitable to be installed in nurseries and schools was guided by the following requisites. It should be:

- Robust and childproof: it should be able to remain permanently installed in a nursery and school, and to be continuously used by children requiring little maintenance between use.

- Large and conformable enough to be used by groups of up to 5 children aged 3-6 years old.

- Cheap and made with common technological components.

The first design decision taken was the size of the playable surface area. To enable up to 5 children playing at the same time, a usable surface area of 110 x 90 cm was established. To allow comfortable use by children, height surface was set at 40 cm.

With these measurements, the work focused on finding an optimal distribution of the optical components of the table: the videoprojector and the camera. Both components have to "view" the surface area (110x90cm), and therefore need to be placed at a distance from the surface that it is calculated from the angle of the optics of each component:

Projector: The chosen projector (Benq MP525ST) has a short throw lens, optimally designed to achieve wide projection areas with minimum distance. The lens optic gives a projection area of 41 cm for 50 cm of projection distance. Knowing the height of the tabletop surface area (90 cm), the projection distance needed is 110 cm.

Camera: The Point Grey Firefly MV camera has an optic of 70º. This is a wide lens angle, but not a fish eye. A fish eye lens would be able to cover the whole table surface with very short distance, but this will give notable image aberrations which would impede fiducial tracking.

With the optic vertical angle of 70º and the target area surface of 90 cm, the distance from the camera to the surface is calculated as 64 cm (see Fig 137) using the formula h = 45 / tang (35º).

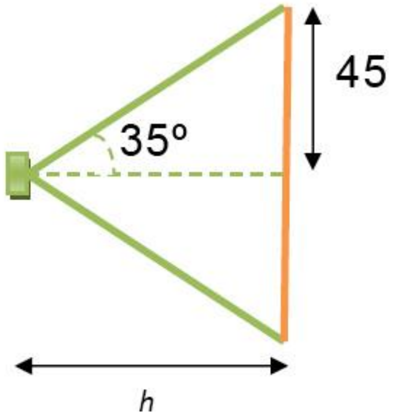


Fig 137: On the left, green box represents the camera. Green cone is the view field of 70º camera lens.

As the height of the surface is fixed at 40cm, there is no way of placing the camera or projector directly looking at the surface from under the table. Thus, a mirror is needed to enable larger projection and camera distances.

The design decision was to place a mirror on the base of the table, and place a camera and projector at the back of the table with enough height to achieve the calculated distances for each component (see Fig 138).

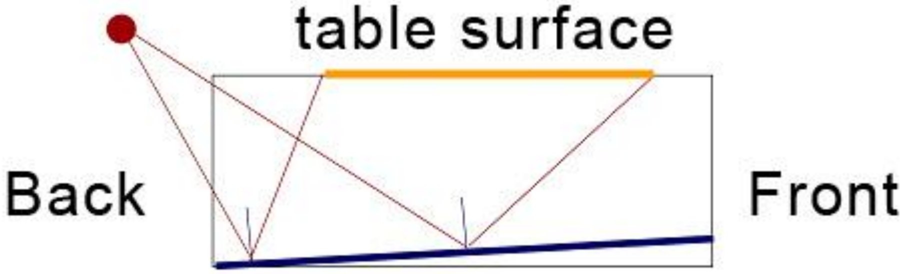


Fig 138: Red circle represents the camera or projector. By pointing the device at a nearly flat oriented mirror on the base of the table, it is possible to cover the entire table surface from below.

With a projection distance of 110 cm and a camera distance of 64 cm, two stands were designed to support each component at the back of the table (see Fig 139 and Fig 140).

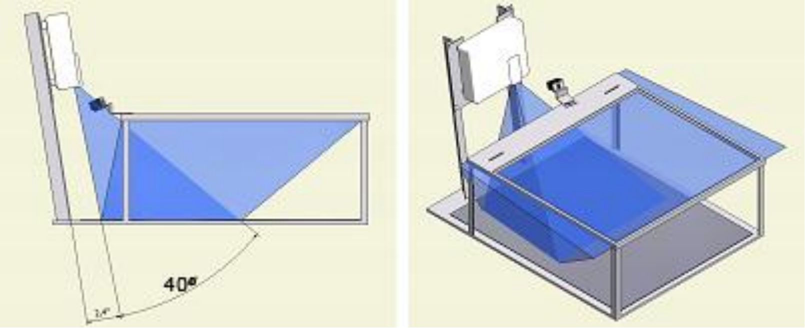


Fig 139: Projector stand to cover the entire table surface.

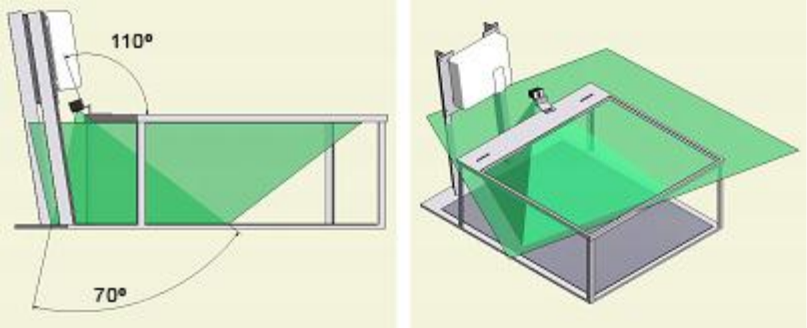


Fig 140: Camera stand to cover the entire table surface.

The construction of the table broken down into its main components (see Fig 141):

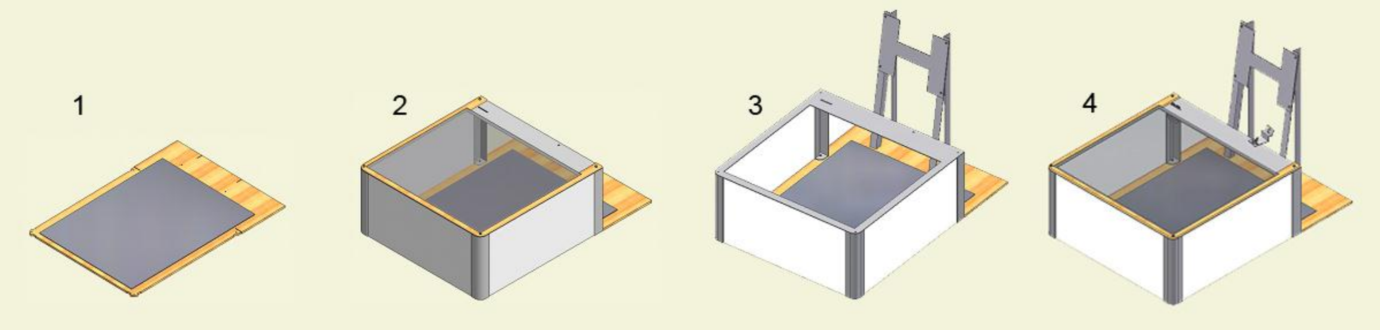


Fig 141: Tabletop structure: 1-base. 2-walls and surface. 3- projector stand. 4- Camera stand

1- Table base:

The base is made of wood with a mirror attached to it. All the components are attached to the base, so, if the table is pushed or dragged on the floor, all the components would move together.

2- Table walls and surface:

The walls are also made of wood, and painted white to maximize the diffusion of IR light. The table surface is made of a wooden frame which supports a transparent Plexiglas surface in which interaction will take place. Plexiglas is a very resistant and unbreakable material, so is optimal for use with children. It has to be kept thin enough to avoid defocus of the fiducial placed on the table. Particularly thick Plexiglas will be very resistant, but the camera would view fiducials as very unfocused and visual recognition would be unreliable. Thin Plexiglas would become deformed with children's interactions, but the camera would capture the fiducial image with no defocus and high reliable tracking. NIKVision tabletop uses a 2.5 mm thick surface. It is a very thin surface which supports very reliable fiducial tracking. It deforms a little when children push very hard, but it is impossible to break, so reliable and safety interaction is guaranteed.

On the underside of the Plexiglas, a translucent acetate for retroprojection is attached. This acts as a light diffuser, giving a clear image projection on the table surface, while enabling the camera to see fiducials through translucent acetate (see Fig 142).

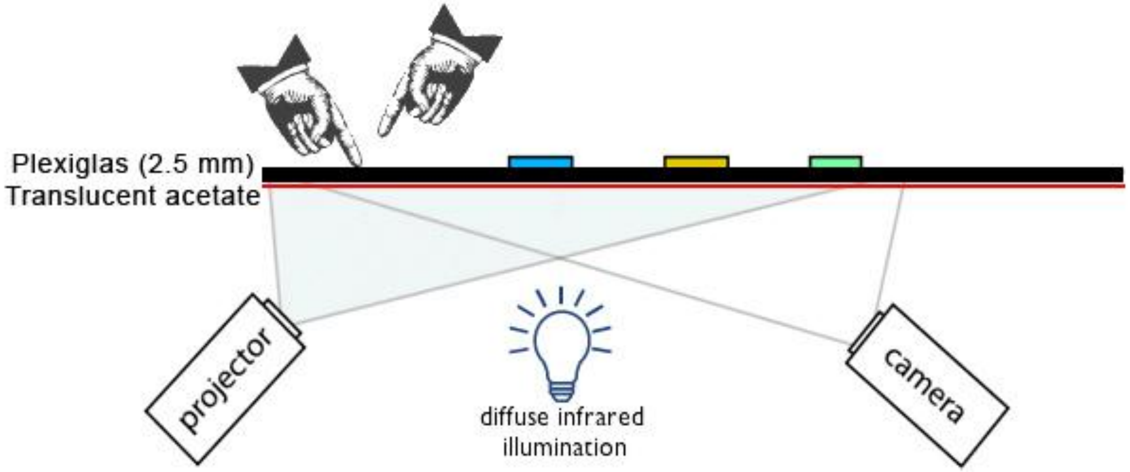


Fig 142: The tabletop surface comprises transparent Plexiglas (black) to give consistency and translucent acetate (red) to enable light diffusion of image projection and avoid IR light hotspots.

Practically it is possible to place acetate on top of the Plexiglas. However, acetate is very fragile and will deteriorate very soon with toys dragging on it. Moreover, Plexiglas would produce bad IR light hotspots on its surface which would distort fiducial recognition. Placing acetate under the Plexiglas acts as a light diffuser, getting rid of IR light hotspots.

3- Projector stand

This consists of a metal structure to screw the projector on firmly and safely (see Fig 143).

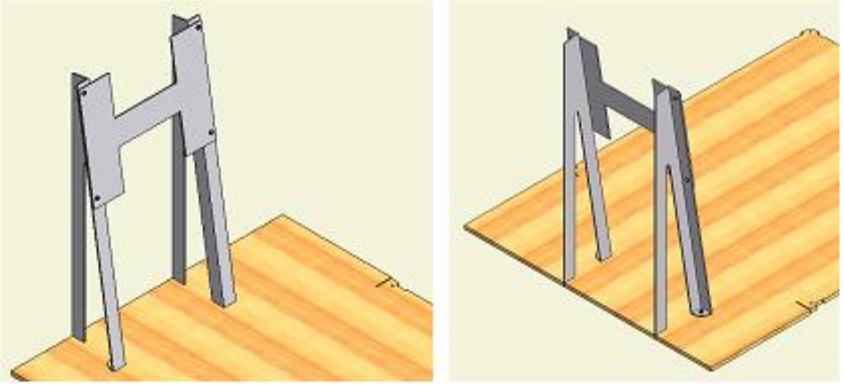


Fig 143: Metal stand to attach projector

4- Camera stand

This consists of a metal stand attached to the back of the surface frame which enables the camera to be screwed onto it.

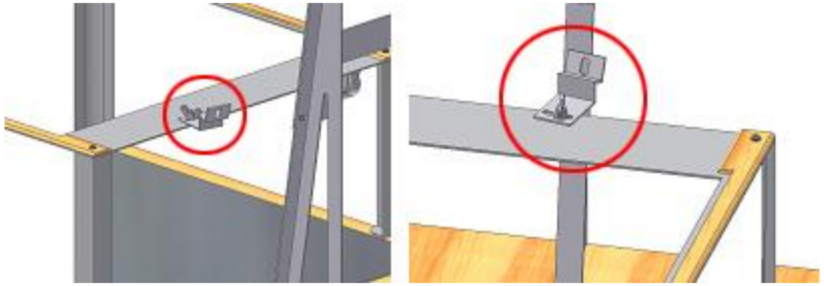


Fig 144: Camera stand

Finally, IR lights are attached on both corners of the back of the surface frame (see). These are placed pointing at the front wall of the table to achieve nice diffuse light.

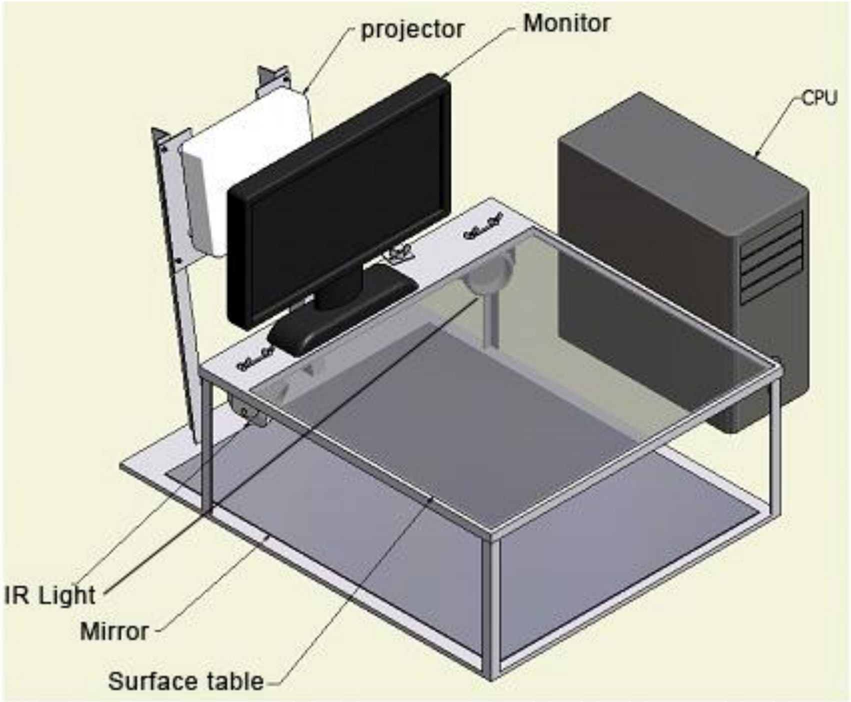


Fig 145: complete tabletop with all components. IR lights are placed back under the table surface frame.

Finally, the table walls were designed to be conformable when children are standing or kneeling near the table. In the initial version, the walls had a gentle slope which allowed children’s feet or knees to go in the table (see Fig 146). Due to the difficulties in making the table structure with sloped walls, finally walls were built with a step in the middle, carrying out the same function of giving room to children's feet or knees (see Fig 147 and Fig 148).

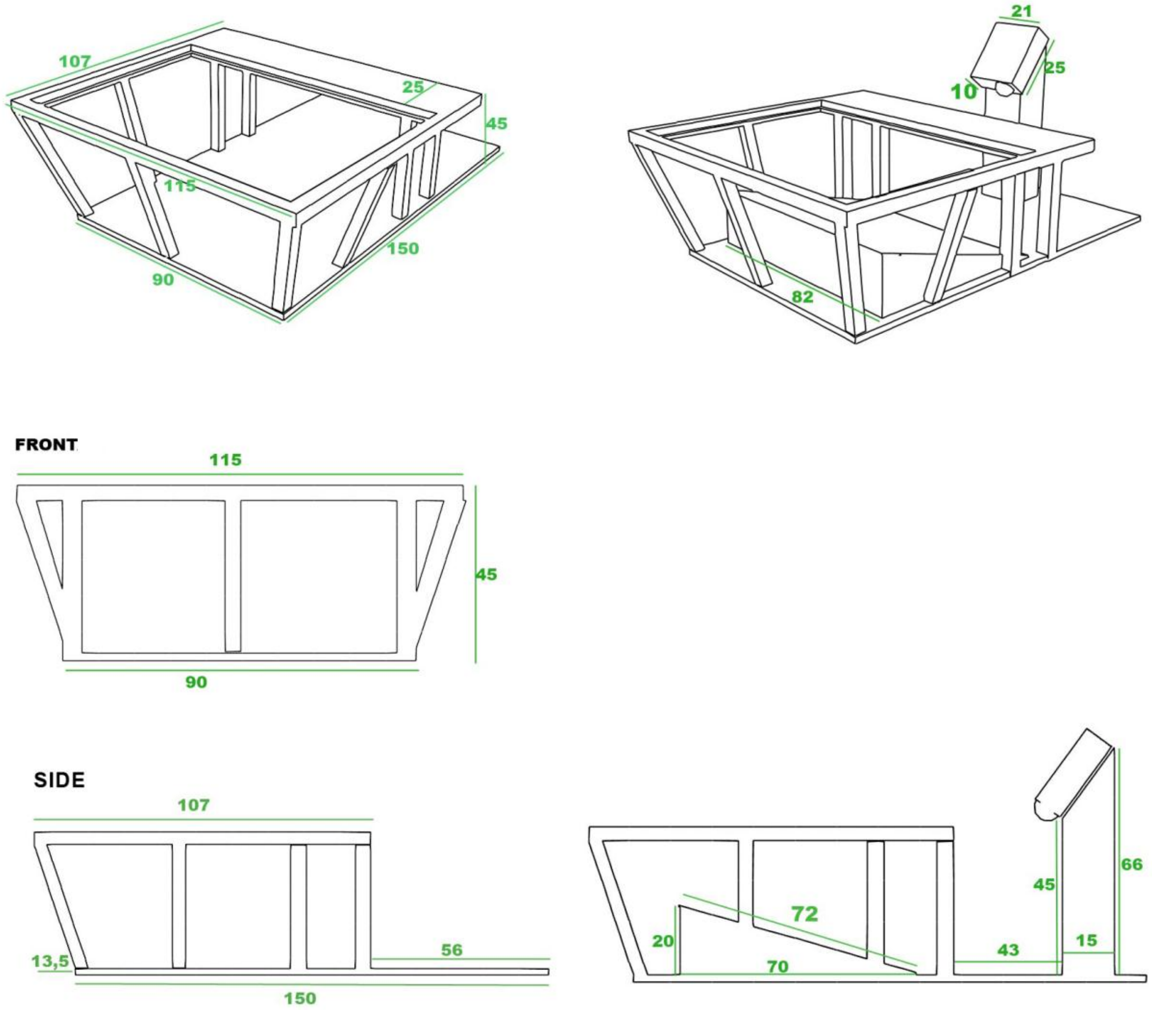


Fig 146: Outline of tabletop design with sloped walls. All dimensions are in mm.

Fig 147: Front view of the NIKVision tabletop, with stepped walls.

Fig 148: Back view of NIKVision tabletop.

Annex 2: Reactivision Framework

Introduction

The implementation of TUI applications for surfaces relies mainly on the computer being able to recognize and track conventional objects. As described in section 2.2.3 this function can rely on:

- Creating electronic hardware which, embedded into objects, would help the computer to "sense" the objects, or

- Creating image recognition software which would enable the system to visually recognize objects, in a similar way that the human eye and brain is able to see and analise objects on a table.

The hardware approach has the advantage of being reliable and robust. It is very computer oriented, based on digital technologies (like RFID tagging), so it is easy to build an electronic system which will recognize and track electronic augmented objects with 100% accuracy. But there are also many drawbacks. Such kinds of electronic devices and computer sensor are expensive and fragile. Embedding electronics in objects and tabletop surfaces involves notable structural changes and wiring, so prototyping such kinds of devices requires technical knowledge and skills which would slow down the evolution of the product and critically raise the budget required to carry out iterative design lifecycles.

The image recognition software approach overcomes all the cons of the hardware approach, but by giving up its advantages. Visual recognition of objects on a tabletop requires little or no intervention on objects. In an ideal situation, a perfect visual computer system should be able to recognize and track any conventional object the same way that humans are able to carry out that function. In a less perfect and more realistic situation, some visual patterns (called fiducials) are attached to the objects, easing the task of visually recognizing the pattern instead of the object itself. But fiducials consist of a simple piece of paper with a printed pattern. Computer augmented objects using fiducials are cheap and easy to create. However, the need of fiducials to support computer recognition of conventional objects is indicative of the present situation of machine vision: camera hardware and image recognition algorithms are still far from being as reliable as the human eye and brain. This is the main disadvantage of using this approach to create a tangible tabletop. If designers of TUI applications had to develop the visual algorithms which perform the requisites needed for the application, this task will probably surpass the development efforts, and if finally the algorithms are not robust enough, this would ruin a great design ideal.

In this context, the framework approach has proven to be an ideal method to enable fast and easy prototyping of the tangible tabletop application by:

1. Being independent software modules which run like a black box, hiding the process of visual recognition from the other functionalities of the application (just as a developer of a GUI application does not have to worry about implement algorithms to retrieve information from mouse and keyboard devices),

2. Being independent of the computer platform or/and development tool used to run or/and implement the tabletop application software. This would widen the scope of designers with great technical knowledge who would be able to develop the applications with the same framework,

3. Being easily adaptable and customizable to nearly all possible designer needs when creating their tabletop applications,

4. Being able to evolve and grow with new capabilities as designers create new ways to interact with a tabletop device.

The Reactivision framework, originally created to support the visual recognition process of the Reactable tabletop, has quickly become the most successful framework for fast and easy prototyping of tabletop applications. As seen in Fig 149, Reactivision retrieves images from the table surface from a camera under the table; it then analises the image, isolating the fiducials and assigning a numerical ID to each different fiducial; with this data, Reactivision elaborates a list of identified objects and sends this over the network using TUIO protocol. This perfectly reflects the four points set out above:

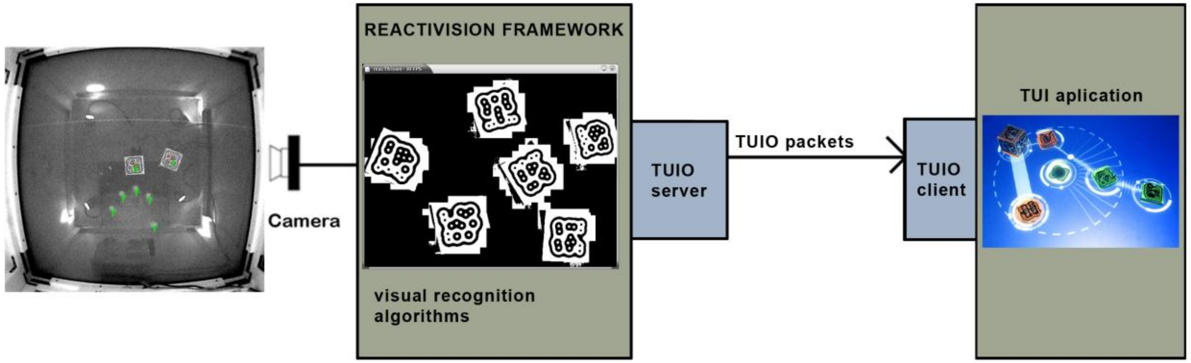


Fig 149: Structure of Reactivision framework.

1. Reactivision is an independent application which is executed as a standalone program. It detects any camera connected to the computers, and starts analising the image seen by the camera. Any application can obtain the information of objects on

the tabletop, by listening to a UDP port. Reactivision uses TUIO open protocol to arrange network packets with this information embedded in them. Any development of a TUI application which uses Reactivision software only needs to implement a simple TUIO client to receive TUIO packets. In this way, the TUI application becomes independent of camera hardware and image recognition algorithms.

2. There are Reactivision implementations for most popular computer platforms. Reactivision is free and can be downloaded from its webpage. Also, there are TUIO client implementations from most development environments, so programmers can download libraries or code to implement a TUIO client in the preferred programming tool.

3. There are lots of parameters which can be changed within the Reactivision interface which free designers from many particularities of their tabletop configuration: image can be calibrated to fix camera lens aberrations, flip or flop to adapt to different mirror configurations under the table, tune thresholding to adapt to particular light conditions, etc.

4. Reactivision and TUI are OpenSource projects. If designers need a capability for the intended TUI application that is not implemented in Reactivision, a C++ project can be downloaded from its website, and programmers can develop new algorithms to expand its possibilities.

For all these reasons, Reactivision was the chosen tool to develop our games in this thesis.

Original Reactivision functionalities

The software version of Reactivision framework was 1.2, from May 2009. The functionalities of this version can be divided in two main groups:

Finger tracking:

When fingers touch the table surface, they receive IR light from the table surface and the camera views the fingers as little circular spots.

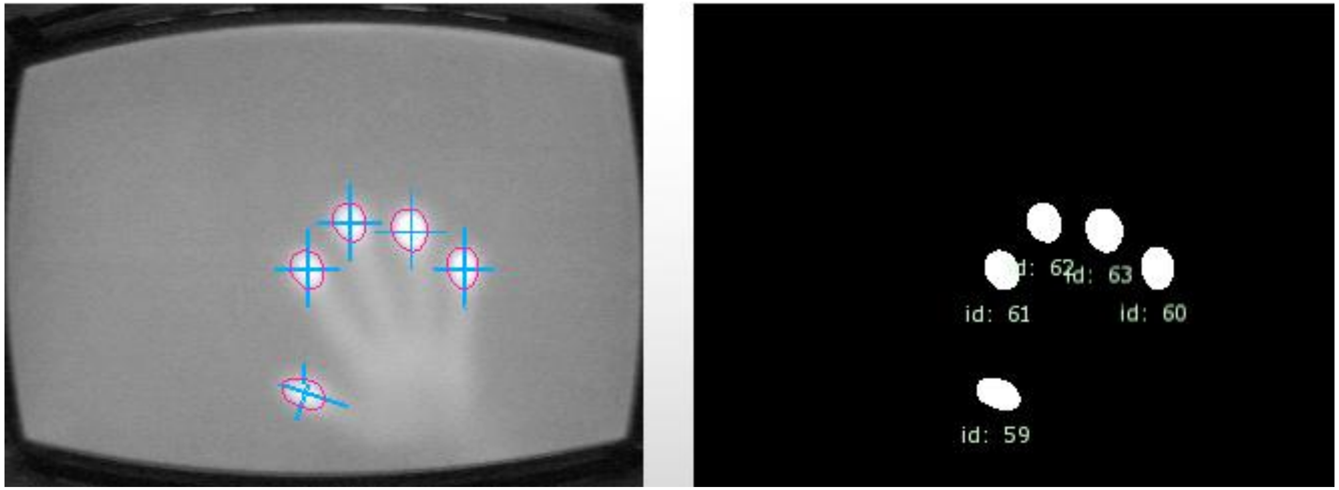


Fig 150: Reactivision finger tracking. Left, fingertips touching the table surface reflect more light than the rest of the surface. Right, by thresholding, Reactivision algorithms can isolate fingertips as white blobs.

Reactivision, tags any small circular white blob as a “finger” object, and draws up a list of finger objects detected in the table, adjoining their 2D coordinates, and refreshes this list in each frame captured by the camera. The finger list is sent to the client application using the TUIO protocol.

This finger functionality was used in the “Math game” and “Drum Sequencer” NIKVision applications (see section 3.4.2 and section 3.4.3). Plastic pieces have a circular shape, and, when placed on the table, Reactivision interprets them as fingers.

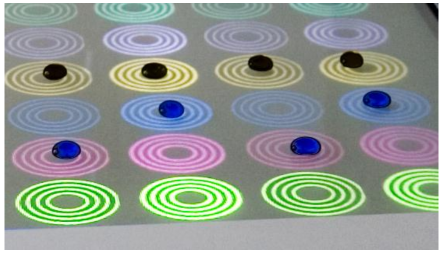


Fig 151: Plastic pieces on the tabletop are detected as fingers by Reactivision visual algorithms

Fiducial tracking:

Reactivision fiducial recognition algorithms are based on the analysis of region adjacency graphs. The thresholded binary image captured by the camera is segmented in 3 level trees of adjacency. Reactivision stores a dictionary of adjacency trees associated with all the possible fiducials that it is able to recognize (see Fig 152). The upper one is the root blob, and is the external area of the fiducial. Black circles represent black blobs which are inside the white area. Those black blobs which have other white blobs inside are branch nodes. Those which have no other blobs inside are leaf nodes. The adjacency tree is internally represented as character arrays. The first letter can be 'w' or 'b' (for white or black), and represent the colour of the root node. Each number represents the level of each blob. Number '0' is the root node, and one is always present. '1' represents the nodes immediately inside the root node. Those which have other blobs inside have '2' numbers after them. All detected adjacency trees matched with an entry of an internal tree dictionary are considered as fiducials, and a numerical ID is assigned.

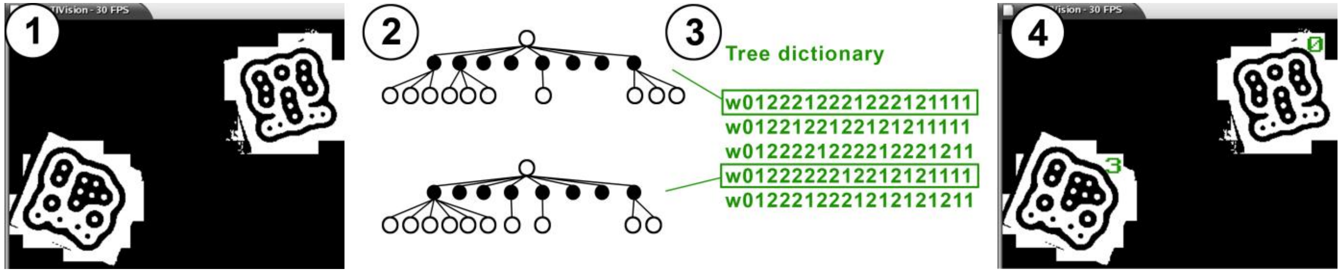


Fig 152: Reactivision fiducial recognition algorithm. 1/ Images captured by the camera are binary thresholded. 2/ 3-Level adjacency tree structure data are built. White circle represents white blobs. 3/ Adjacency trees are translated into text chains. Detected trees are matched with the internal dictionary of Reactivision. 4/ Each detected fiducial is tagged with a number which corresponds with the position of the fiducial in the internal dictionary

Each detected fiducial is also characterized by its position on the table (weight center of the root blob area) and its orientation. Fiducial orientation is calculated by the vector defined by the weight center of the white leaf nodes and the weight center of the black leaf nodes.

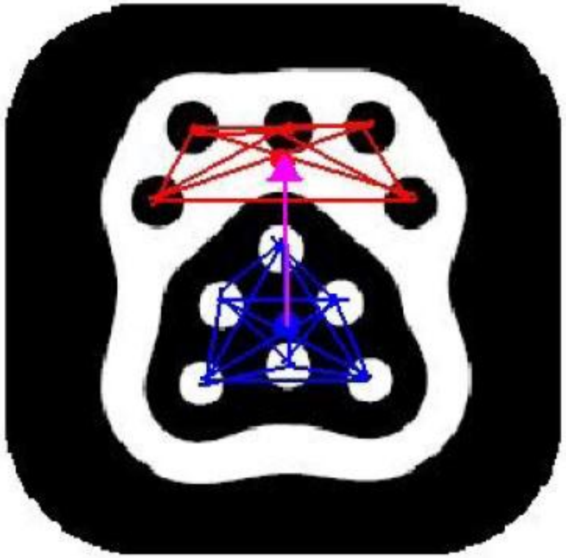


Fig 153 Fiducial orientation is calculated with the vector which connects the weight centre of white leaf nodes (in blue colour) and the weight center of black leaf nodes (in red colour).

This capability of Reactivision framework was used to implement the Farm Game for our NIKVision tabletop (see section 3.3). Each rubber animal toy has a printed fiducial attached to its base (see Fig 154). In this way, when a toy is placed on the table surface, Reactivision sends TUIO packets with a list of all recognized fiducials, with their 2D position on the table and their orientation. Virtual 3D animals are then mapped with the same position and orientation in the virtual farm environment.

Fig 154: Reactivision fiducials attached to rubber animal toys.

Expanded Reactivision functionalities

The open nature of Reactivision framework has allowed us to adapt its original possibilities to our particular needs in the creation of our games for children. Two main functionalities have been adapted during our research:

1. Fiducial personalization:

Any binary pattern which can be translated to a 3-level adjacency tree is suitable to be used as a fiducial in Reactivision (Costanza and Huang, 2009). More complex fiducial designs (number of nodes in the tree) is used when many different fiducials must be detected by Reactivision. The default internal Reactivision dictionary is able to recognize 412 different fiducials. It is very hard to conceive a tabletop application which needs to recognize 412 different objects. For this reason, Reactivision allows the internal dictionary to be changed. Elaborating a dictionary with simpler fiducials (less nodes) reinforces the reliability and robustness of the visual recognition algorithms, decreasing detection errors.

As the number of different toys used in NIKVision was very limited, it was decided to optimize fiducial design to achieve better performance of Reactivision tracking. The Farm game has only four different toys. Thus, a very simple dictionary of fiducials was used (see Fig 155) which allows up to 12 different fiducials, enough to the game requirements. This notably improved the performance of Reactivision recognition.

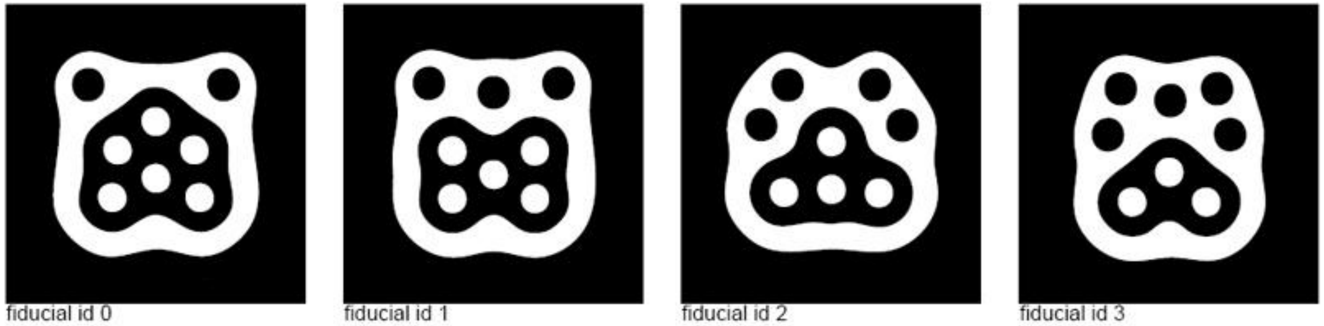


Fig 155: Simplified set of Reactivision fiducials for the Farm game

In the games which only need two different toys, like "Asteroids" and "Pirates!" (see sections 3.4.5 and 3.4.6), a more simplified fiducial dictionary was created. Thanks to these simple fiducials, very small sized fiducials can be printed and adapted to the base of the toys (see Fig 156).

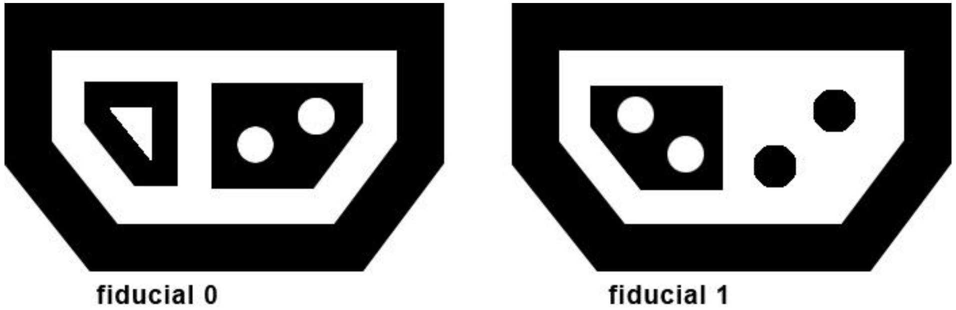


Fig 156: Simplest Reactivision fiducials created for Asteroids and pirates games.

Finally, in the "Draw" game (see section Draw game 3.4.4) a Reactivision fiducial was inserted in a corner of the papers, so the system is able to detect when the paper is placed on the table (see Fig 157). During tests of this game with children, many of them asked for the meaning of the fiducial drawing. In the other NIKVision games, fiducials are attached under the toys, and thus children do not notice the fiducial. But in the "Draw" game, children make their drawing on the same face when the fiducial is printed, arousing their curiosity.

Fig 157: paper with Reactivision Fiducial on a corner

A fiducial with a visual appearance with meaning for children was designed with, at the same time, a valid Reactivision topological tree structure (see Fig 158). The design of the fiducial has the visual appearance of a pen. It can be translated into a 3-lever adjacency tree to be used as a Reactivision fiducial, and the weight center of black and white root nodes defines a vector which Reactivision uses to track the orientation of the paper on the tabletop.

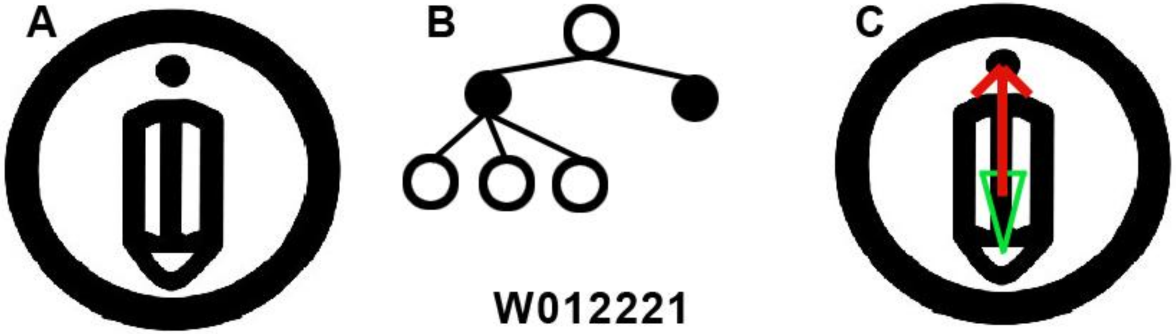


Fig 158: “Draw” game fiducial. A: Fiducial design reminds us of a pen. B: Fiducial tree. C: Orientation vector.

Fig 159: New paper design used in the "Draw" game

Opening the personalized definition of the adjacency trees, the dictionary has allowed us to adapt the fiducials to the game requirements, optimizing game performance and user experience.

2. Drawing capture

The "Draw" game requires a functionality not supported by Reactivision Framework: the drawing on the paper must be digitized and translated to the virtual game environment through videoprojection over the tabletop surface. Since Reactivision is an open-source project, it is possible to program this new functionality directly in the original C++ code of Reactivision.

A new function was implemented which is activated when Reactivision detects a specific fiducial (the one printed on the paper in the game). The workflow of the function is (see Fig 160):

1. The captured frame is stored in a binary array.

2. Using the orientation (ɑ) of the detected fiducial, the image array is rotated in order to horizontally orientate the paper drawing

3. The 2D coordinates (i,j) of the detected fiducial are translated to the new coordinate system into (i’,j’) new coordinates which resulted from the previous rotation using the 2D rotation matrix

4. Using the predefined dimensions of the paper (see Fig 161) and the new (i’,j’) 2D coordinates of the fiducial, the area of the paper is translated to a new binary array, which should contain only the paper drawing. The drawing dimensions are parametrical, so they can be changed for different paper formats

5. Some cleaning of the image borders is performed to achieve a perfect image of the drawing captured.

6. Finally, the cleaned binary array is stored in a hard-drive in BMP file format, and a TUIO message is sent to the game application.

7. When the game application receives the TUIO message, it loads the BMP image and shows it on the table surface. This way the children can pass their drawings to the game environment.

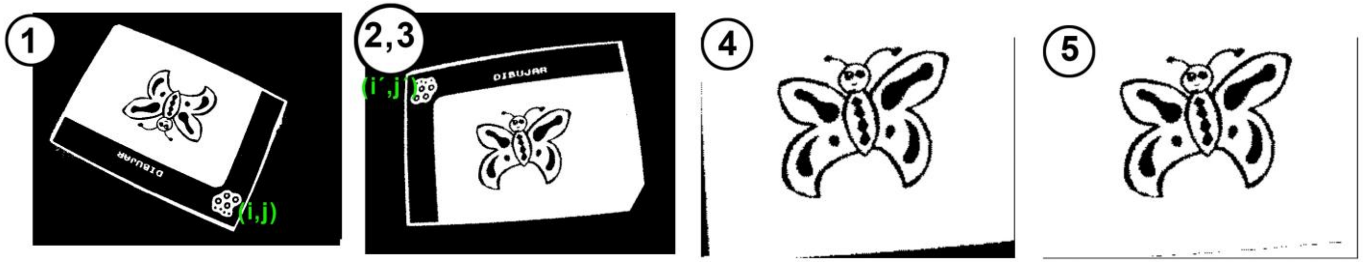


Fig 160: Draw capture process. 1/ Original camera captured frame. 2/ Image is rotated using the angle of the fiducial. 3/ Original 2d coordinates of fiducial are translated in the new coordinates system. 4/ The drawing area is selected and cut from the frame. 5/ Some border cleaning is carried out.

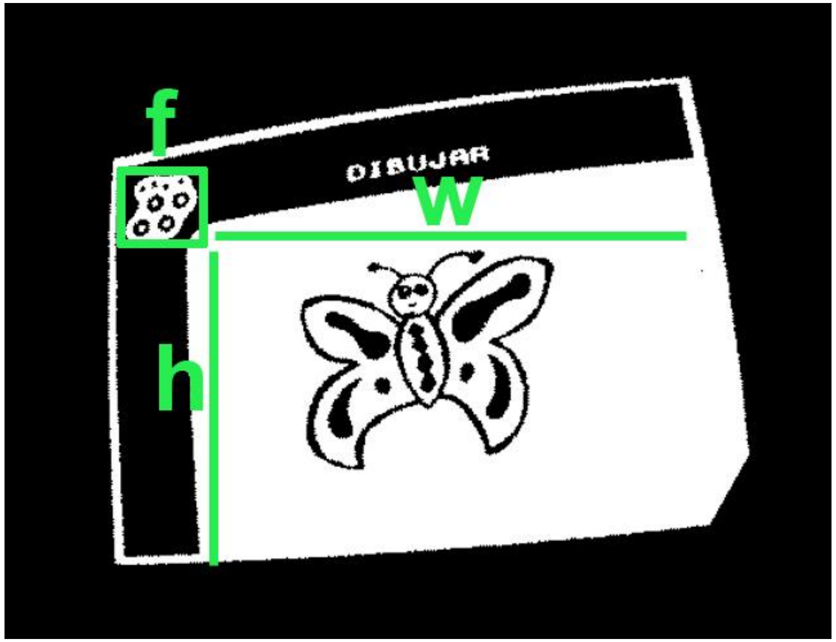


Fig 161: Parametrizable dimensions of drawing. f: fiducial dimension. W: drawing width. h: drawing height.

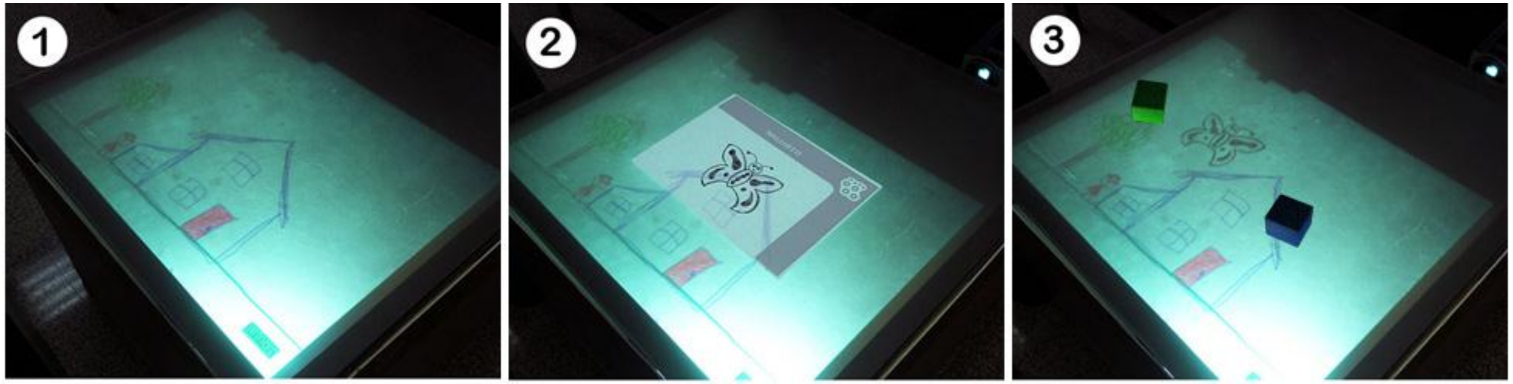


Fig 162: 1: Tabletop virtual environment. 2: Physical paper placed on the table surface. 3: the drawing is “captured” and integrated as a virtual representation.

3.-Hand tracking

Reactivision has multitouch functionalities. However, young children prefer to interact with a tabletop using their hands, crudely hitting and dragging virtual elements on the table surface. A new functionality in Reactivision was implemented to detect and track hands on the table surface.

Hands are seen by Reactivision as big white blobs (see Fig 163). Parameters were added to Reactivision to define a minimum and maximum area for a white blob. Any blob whose area is between the interval is considered a hand. A list of detected hands is built in each frame and sent by TUIO to the game application.

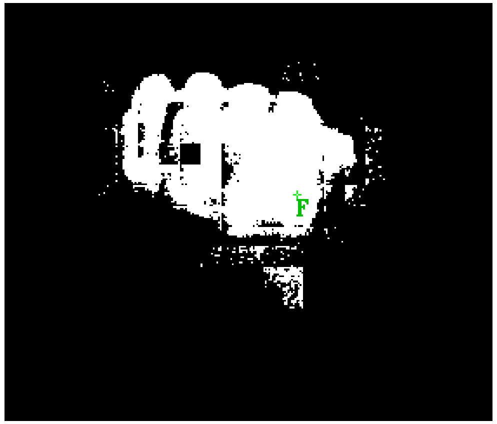


Fig 163: A hand on the table surface is seen in Reactivision as a white blob.

The hand detection functionality was used in the “Draw” game to let the children hit and drag their virtual drawings (see Fig 164).

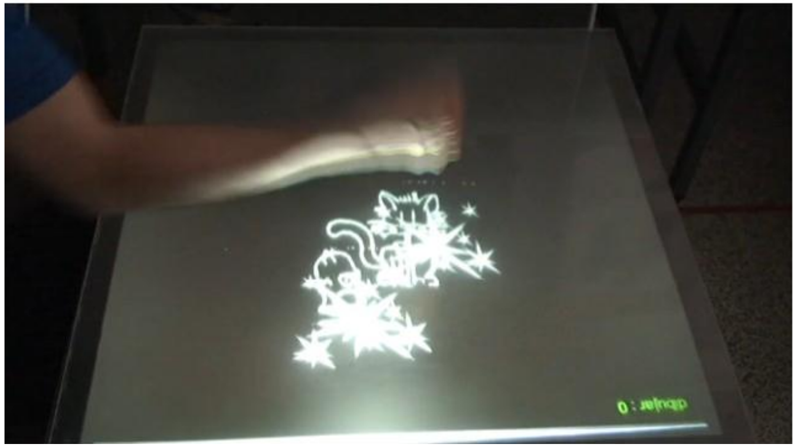


Fig 164: Virtual drawings hit with the hand.

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