Discovery learning with tangible technologies: the case of children with intellectual disabilities

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Abstract

Intellectual disabilities cause significant sub-average achievement in learning, with difficulties in perception, attention, communication of ideas, language acquisition, abstraction and generalisation. From a socio-constructionist perspective, digital technologies can provide resources to help addressing these difficulties. Tangible technologies are considered particularly promising tools for children with intellectual disabilities, by enabling interaction through physical action and manipulation and facilitating representational concrete-abstract links by integrating physical and digital worlds. However, hands-on learning activities remain a recommended but problematic approach for intellectually disabled students. This thesis investigates how and which characteristics of tangible interaction may support children with intellectual disabilities to productively engage in discovery learning.

Empirical studies were performed where children with intellectual disabilities used four tangible systems with distinct design characteristics. Four broad themes emerged from qualitative analysis which are central for identifying how to best support exploratory interaction: types of digital representations; physical affordances; representational mappings; and conceptual metaphors. Guidelines for the development of tangible artefacts and facilitation of discovery learning activities with tangibles were derived from these themes. A complementary quantitative analysis investigated the effects of external guidance in promoting episodes of discovery in tangible interaction.

This thesis argues that providing tangible interaction alone is not sufficient to bring significant benefits to the experience of intellectually disabled students in discovery learning. Visual digital representations, meaningful spatial configurations of physical representations, temporal and spatial contiguity between action and representations, simple causality and familiar conceptual metaphors are critical in providing informational intrinsic feedback to exploratory actions, which allied with external guidance that creates a minimal underlying structure for interaction, should establish an ideal environment for discovery.

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I grew up with Pedro. Since his birth, I have been watching him struggle in life. My brother kept changing schools and fighting the world, and could never do his maths homework, as hard as I tried to teach him. No precise diagnosis was given by doctors, and no causes were ever more than possibilities. Pedro could never adjust to our middle class, intellectual family. He could never reach us and we could never reach him. But most of all, he could never fully benefit from the school environment. Pedro now works in a shop and is getting married next year. This thesis is for him, and for all other Pedros that are now in school, or are yet to be born. Perhaps - who knows - this work can help them do their maths.

As lonely a journey as it can be, a PhD involves more people than it may seem. I would like to thank my supervisor Dr. Sara Price for accepting me as a student when I first came to London, welcoming me at the London Knowledge Lab and offering me my first cup of English tea. I would like to thank her as well for the constant support, for providing the materials and infrastructure that were crucial for this research, helping out with the empirical studies, revising the thesis in detail throughout all phases of the work, and for understanding when I needed time to think. I would also like to acknowledge the fantastic opportunity of having Professor Diana Laurillard as a co-supervisor, and thank her for taking the time to read this work and contribute with all her experience. Thanks to Professor Carey Jewitt, Dr. William Farr and Wedad Al-Gawhary for their most generous help in conducting the empirical studies and thanks to all staff of the London Knowledge Lab for their patience when we had kids running all over the place. A very special thanks to these kids and their teachers, who made efforts to take voluntary part in this research. It goes without saying that their contribution was priceless and fundamental to this work. I really hope our joint efforts contribute to the future scenario of special education.

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Life goes on while you do a PhD. I am now a passionate lecturer at the Brazilian university UFRPE, and would like to thank my dear students for their support and patience when I could not be there for them because I was finishing my thesis. Thanks also to my colleagues at UFRPE for sparing me from admin work and for the classroom replacements during the final months.

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Declaration

I hereby declare that, except where explicit attribution is made, the work presented in this thesis is entirely my own.

Signature: Taciana Pontual R Falcão   Date: 1st of September 2014

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Table of contents

List of figures

List of tables

"(...) not just with what kind of technology we use, or with what sort of interactions we engage in with that technology, but (...) what makes those interactions meaningful to us."

(Dourish, 2001, p. 53)

"We can't say that a certain student doesn't learn. Every creature in the world learns, they just need to be stimulated, sometimes in different ways."

(Teacher interviewed)

Chapter 1 - Introduction

In the name of the law of Ancient Greece, and in agreement with great philosophers, children born with deficiencies were to be 'disposed of' (Aristotle, 350 B.C.; Plato, 360 B.C.). During the Christian period, neglect and mistreat slowly evolved into pity and a kind of protection of the disabled that meant their isolation in colonies, for their own benefit and the majority's (Read and Walmsley, 2006; Thomas and Loxley, 2007). In the United Kingdom, the once labelled 'ineducable' were granted the right to school education no sooner than 1970 (Read and Walmsley, 2006). Since then, changes in philosophical perspectives have directly influenced pedagogical approaches for these children's education. Recently, there has been a move towards a social model where deficiencies are no longer seen as immutable and solely located in the individual, but socially constructed through the interaction of the child with the environment (Slee, 1998; Soder, 1989). According to this perspective, adopted in this thesis, learning disabilities can be diminished or overcome if adequate tools are provided and appropriate conditions are set up in the environment. Ultimately, the efforts to improve education of children with intellectual disabilities aim to help them to become social participants and adult wage earners, included in the community and no longer rejected by society (Kirk and Gallagher, 1979).

Providing appropriate environment and tools to improve the life of children with intellectual disabilities has proved to be a great challenge for educators and policy-makers. There is little evidence that diagnosis of medical conditions calls for syndrome-specific types of educational interventions and specific diagnosis often becomes irrelevant to the everyday practice of teachers (Kirk and Gallagher, 1979; Mittler, 2000; Vaughn and Fuchs, 2003). In the classroom context, where the tendency towards inclusion is fast increasing (Lindsay, 2007), interventions must be directed to heterogeneous groups of intellectually disabled children, focusing on their common characteristics, which include difficulties in perception and attention, judgement and reasoning, social communication, and abstraction and generalisation.

A type of intervention that is typically recommended for children with intellectual disabilities follows a constructivist hands-on approach, based on concrete experiences and physical interaction with the phenomena in study (Bell, 2002; Cawley and Parmar, 2001; McCarthy, 2005; Scruggs and Mastropieri, 1994). However, this approach also brings difficulties related to poorly structured activities, concrete-abstract links, and open-ended tasks, usually involving permanent coaching that poses high demands on teachers (Scruggs et al., 1993). A parallel trend for providing support for intellectually disabled students advocates the use of digital technologies, believed to encourage creativity and initiative, create sense of achievement and improve concentration and motivation (DES, 1991; Hawkridge and Vincent, 1992). Nevertheless, the current use of digital technologies for intellectually disabled students in schools is criticised for focusing on drill and practice rather than on discovery and creativity (Keay-Bright, 2008), and for lacking interaction with the physical world (Eisenberg et al., 2003).

The advent of tangible systems, which embed digital resources in physical objects, has brought possibilities for re-engaging with physical materials without losing the avowed benefits of digital technologies. Tangibles are known as a particularly accessible type of exploratory technology, due to their potential intuitiveness, usability and multimodal sensorial engagement (Zaman et al., 2012). However, research in the tangibles field is still in its infancy, calling for a better understanding of the implications of linking the physical and digital worlds (Shaer and Hornecker, 2010). Many designers have concentrated on increasing the technical functionality of dynamic visualisations focusing on the 'wow factor' and leaving learning processes aside, which create artefacts of limited educational value (Chandler, 2009). The possibilities, advantages and drawbacks of bringing tangibles into the learning process compose a field in need of further research, particularly in the case of children with intellectual disabilities (Shaer and Hornecker, 2010; Zaman et al., 2012). So far, incipient empirical studies with tangible interfaces and the population of special educational needs (SEN) have indicated positive effects on engagement, collaboration and initiative, although most accounts remain anecdotal.

The present research aimed to investigate how and which characteristics of tangible interaction may support children with intellectual disabilities to productively engage in exploratory, hands-on activities of discovery learning, overcoming difficulties like lack of structure, open-endedness and construction of concrete-abstract links. The thesis is organised as follows. Chapters 2, 3 and 4 establish the interdisciplinary field of the work, the context where it is situated, and its theoretical foundations. Chapter 2 gives an overview on special educational needs, situating intellectual disabilities in the SEN field through philosophical perspectives and definitions from different domains. It also explains the situation of SEN within the school context in the United Kingdom, which is part of the motivation for this work and provides the reasons for some methodological choices. Chapter 3 presents the theoretical foundations of the thesis, which draws on constructivism and embodied cognition to advocate learning through discovery with physical artefacts. The chapter also discusses the role of digital technologies as external representations that can act as mediators of the discovery learning process. Chapter 4 starts with a discussion of the concept of tangible technologies, situated within the tangible interaction paradigm and its evolution, followed by theoretical considerations developed so far on the potential benefits of tangibles for learning, and in particular for special educational needs.

Chapters 5, 6 and 7 cover methodological considerations and choices, and detail the procedures of the empirical research. Chapter 5 presents the methodology and research techniques adopted, explaining the structure and aim of the two phases of the research and their relationship. Chapter 6 describes the first phase (field research in schools), which aimed at better understanding the context and the needs of children with intellectual disabilities and their teachers. Results from this phase informed the design of empirical studies where children with intellectual disabilities were asked to explore four different tangible technologies: the interactive tangible tabletop, the d-touch drum machine, the Sifteo cubes and the augmented object. These studies, which represented the core of this work, are described in detail in Chapter 7.

Analysis of the data from the empirical studies is presented in two parts (Chapters 8 and 9). Chapter 8 presents a holistic qualitative analysis of child-tangible interaction, in terms of how different characteristics of tangible technologies can support or hinder the process of discovery learning for intellectually disabled students. This discussion is structured around four broad themes related to tangible interaction, which emerged as relevant for the context of intellectual disabilities, namely: types of digital representations (which here could be textual, auditory or visual); physical affordances (including perceived versus designed affordances of tangibles, possible spatial configurations of sets of objects, and different roles of action in exploratory interaction); representational mappings (couplings of action and effect, and between distinct representations); and conceptual metaphors. Considering all these aspects, among the four systems analysed the tabletop was found to have the best design features for supporting children with intellectual disabilities in exploration. For this reason, data from the empirical sessions with the tabletop were coded and quantitatively analysed, as described in Chapter 9. Findings indicated the main contributors and obstacles in exploratory tangible interaction for leading children through different forms of comprehension. Finally, Chapter 10 concludes the thesis summarising its main contributions and limitations, and pointing to future work.

The sequence of chapters of the thesis builds up a narrative that reflects an evolving and dynamic qualitative research process, based on serendipity and discovery, where the object of investigation was constructed and refined progressively, and studies aimed not only to find answers, but also to encounter questions. More than simply learning about a topic, the goal of the work that follows was to learn what is important for those being studied.

Chapter 2 - Special educational needs

The generic term 'special educational needs' (SEN) has been widely used in the United Kingdom (UK) for nearly thirty years to refer to difficulties that affect learning, behaviour, emotional and social development, communication, and ability to care for self and gain independence (Lindsay, 2007). Children with SEN have a significantly greater difficulty in learning than the majority of children of the same age, or a disability that hinders them from making use of educational facilities provided for children of their age (DfES, 2001; Kirk and Gallagher, 1979). A special educational need implies the existence of a gap between a child's achievement and what is expected of them, which is generally represented in terms of curricular aims (Stakes and Hornby, 2000; Wedell, 2003). Such gap can be due to physical, sensory, or emotional-behavioural difficulties as well as learning difficulties (Woolfson and Brady, 2009). Different social and educational policies and strategies have been adopted throughout the years, reflecting changes in dominant philosophical perspectives on the causes of learning difficulties and on the most adequate approaches for these children's education. This chapter presents the historical development of such perspectives and policies, and attempts to describe the general characteristics of children said to have intellectual disabilities, who are the target group of the present research. Such group is problematic for lacking a precise definition, but nonetheless represents the largest reported group of children with SEN in schools in the UK, thus representing a great challenge for educators and policy-makers who struggle to provide appropriate environment and tools to improve these children's life.

Philosophical perspectives

A number of philosophical perspectives attempt to locate the origins and reasons for learning difficulties. Essentialism (Slee, 1998) takes on a medical / clinical view (Soder, 1989) to locate children's disabilities in their individual pathology, i.e. being a biologically determined defect internal to the child (Khamis, 2009; Kirk and Gallagher, 1979). Aligned with this 'within-child' perspective are the normative and developmental models of special education. The normative model provides the basis for identifying educational needs by assessing children's achievements through standardised tests designed for their chronological age, such as Intelligent Quotient (IQ) tests. Until relatively recent times, this was a dominant approach, and IQ test scores were seen as accurate and immutable measures of the learner's potential, and used to classify learners as educationally 'subnormal' or 'normal' (Abbott, 2007). Also within the essentialist perspective, the developmental model considers achievements per sequential stages in a child's development (the Piagetian stages being the most well-known (Piaget, 1970)) to identify needs, usually as gaps in the expected sequence of development (Wedell, 2003). These two models are descriptive, in the sense that they give accounts of the characteristics of the children, according to specific criteria. Other models attempt to give explanations, rather than descriptions, for poor intellectual achievement. The organic model presents neurophysiologic explanations for a child's intellectual performance, i.e. causes for low achievement can lie in defects of the nervous system (Soder, 1989). Closely related, functional models attempt to define the neurophysiologic functions needed for performing tasks at different stages of development (Soder, 1989).

Criticism on essentialism argues that person-centred views of human behaviour cannot account for all situations. According to Wedell (1990), special educational needs are not caused solely by factors within the child, but are an outcome of the interaction between the characteristics of the child and the resources and deficiencies of the environment. The medical model predetermines children to poor academic achievement due to their own deficits, taking no account of the deficiencies of the educational environments and placing the burden uniquely on the constitutional nature of the individual (Abbott, 2007; Kirk and Gallagher, 1979).

Social constructionism is an opposite epistemological perspective which emphasises the importance of culture and context, and according to which knowledge is not discovered, but constructed through interactions of individuals within society (Schwandt, 2003). Socialisation takes place through significant others who mediate the objective reality of society and make it meaningful to be internalised by individuals (Berger and Luckmann, 1991). Each individual's identity thus originates from the social realm, and not from inside the person (Burr, 2003). Therefore, a socio-constructionist view on disability sees it as a socially contrived construct, derived from social values and beliefs (Slee, 1998; Soder, 1989). Social constructionism is closely related to Vygotsky's developmental theory, which argues that an intellectual disability is not solely a natural deficiency, but also a phenomenon of cultural deficiency (Vygotsky and Luria, 1993). Although a certain disability may exist as an independent reality, the determination of *what constitutes a disability* is socially constructed (Andrews, 2012).

Socio-constructionist descriptive models analyse the communication among students and with the teacher. According to explanatory attitudinal models, a child's role within a group, labelling, and the expectations of others have a critical impact on their attitude, outlook on themselves and capability to learn, therefore affecting their performance (Wedell, 2003). Other socio-constructionist explanatory models (e.g. applied behavioural analysis) analyse the type of instruction delivered, considering aspects like motivation and feedback for the student. System models provide theories taking into account organisational and structural aspects of schools, and how they impact on students' performance (Wedell, 2003). Such models are also related to the adaptability approach, according to which disability arises from maladaptation of the individual to the environment (Kirk and Gallagher, 1979; Soder, 1989).

Social constructionism thus sees disability as a status in a social system (Kirk and Gallagher, 1979). It is important to note that it is in the school environment that children with learning disabilities are defined as such (Khamis, 2009). Students with learning difficulties can interpret feedback from teachers and peers as indication that they are less capable (Chapman, Lambourne and Silva, 1990). The Six-Hour Retarded Child report (1970) from the Committee on Mental Retardation in the United States declared that some children are only said to have intellectual disabilities from 9 am to 3 pm, i.e. during the time when they are at school. When in their neighbourhood or familiar settings, these same children might fit in as typical. In other words, someone can be considered disabled in one community / context, and not in another, or have temporary or transitory disabilities, at one stage of their life only (Abbott, 2007; Kirk and Gallagher, 1979).

Recently, there has been a general move away from the medical model of learning difficulties to the social model, where learning is socially situated. Deficiencies are no longer seen as immutable and solely located in the individual. The focus has moved from the problem *of the child* to the way in which the classroom or school is set up (e.g. inappropriate grouping of students, inflexible teaching styles, inaccessible curriculum materials, insufficient resources), hindering learning for some children (Abbott, 2007; Dockrell, Peacey and Lunt, 2002). A number of researchers have noted that the classroom environment contributes significantly to behavioural and emotional problems (Jones and Jones, 2001; Lerner, 2000). More broadly, child poverty, poor childcare, social and economic deprivation, and family circumstances are also factors that affect the child's achievement in formal education. Chaotic family environment and other characteristics associated with low-income classes may contribute to intellectual disabilities (Kirk and Gallagher, 1979). The shift to this social constructionist perspective has been at the root of much of the progressive thinking behind moves to inclusive education, encouraging a diversification of the social, material and cultural contexts in which all children can be enabled to learn (Abbott, 2007; Thomas and Loxley, 2007).

The present research is aligned with a socio-constructionist view, considering learning difficulties as a product of the interaction of the child with the environment. Such difficulties are thus not immutable, and can be diminished and / or overcome, if adequate tools are provided and appropriate conditions are set up in the environment. The specific focus of the research lies in contributing for providing novel technological tools that may improve learning for intellectually disabled students.

Policies and classifications

Since the times of the Spartans, when the malformed child was killed at birth, society has slowly changed its view on people with disabilities. Great philosophers like Plato and Aristotle agreed with the law according to which children that were born with deficiencies should be hidden or 'disposed of', and by no means reared (Aristotle, 350 B.C.; Plato, 360 B.C.). The Christian period succeeded such era of neglect and mistreat of people with disabilities replacing these attitudes by pity and protection. In the eighteenth and nineteenth centuries, specific institutions were provided for care of the disabled (Kirk and Gallagher, 1979). In the beginning of the twentieth century, when essentialism was the dominant philosophical perspective on learning difficulties, children with special needs in the UK were considered to have a genetic feeble-mindedness that could not be eradicated by education, and therefore were isolated in mental deficiency colonies or other kinds of institutional care, for their own benefit and for the benefit of the 'majority' (Read and Walmsley, 2006; Thomas and Loxley, 2007).

In 1959, the term 'ineducable', used to label these children, was abandoned, and in 1970, children with intellectual disabilities were granted the right to school education in the UK (Read and Walmsley, 2006). Since then, the government has been trying to make education more innovative and responsive to the diverse needs of individual children (DfES, 2004), aligned with a general worldwide philosophy of integrating people with disabilities into society "to the fullest extent possible" (Kirk and Gallagher, 1979, p. 5). The Warnock report (DES, 1978) formally introduced the concepts of special educational needs and inclusive education, defending that "no child should be sent to a special school who can be satisfactorily educated in an ordinary one" (Chapter 7, Paragraph 7.2). Following policies reinforced inclusion, such as the Code of Practice on the Identification and Assessment of SEN (DfE, 1994), the Green Paper 'Excellence for All Children - Meeting Special Educational Needs' (DfEE, 1997), the Programme of Action for Meeting Special Educational Needs (DfEE, 1998), a statutory statement on inclusion into the National Curriculum (QCA, 2000) and the Special Educational Needs and Disability Act (2001). In parallel, SEN became a significant and growing area of public expenditure (AuditCommission, 2002).

Historically, establishing acceptable criteria for identifying learning disabilities has been highly controversial (Vaughn and Fuchs, 2003). The instruction of students with learning difficulties has been marked by a persistent attempt to identify underlying processing deficits associated with specific disabilities, measure intellectual functioning, label the students and subsequently design and implement instructions to remediate those deficits (Lyon, 1985). From an essentialist perspective, a child's ability to learn and achieve well academically is determined by their cognitive ability. The best-known measures are the IQ tests, used for documenting ability in oral and written expression, listening comprehension, reading skills, and mathematics calculation and reasoning, among others (Vaughn and Fuchs, 2003). However, the use of IQ tests is criticised for being paradoxical (Ceci and Liker, 1986; Vaughn and Fuchs, 2003), as they provide 'predictions' of performances within an educational system that aims to 'change' a child through teaching. In other words, there is a contradiction between the stable nature of the psychometric properties evaluated by IQ tests and the dynamism of a child's potential for learning (Kozulin, 2003). Furthermore, IQ tests are not immune to cultural and environmental factors: acquired cognitive abilities depend not only on mental capability but also on environmental challenges and opportunities (contextual variables) (Ceci and Liker, 1986; Stakes and Hornby, 2000). Individuals with low IQs may exhibit high cognitive abilities in non-academic settings, while those with high IQs may have less cognitive ability in non-academic matters due to environmental challenges (Ceci and Liker, 1986).

The use of IQ tests has been reduced in the UK (Lindsay, 2007), reflecting the move from essentialism to socio-constructionism. Nevertheless, few ideas for defining intellectual disabilities have been suggested to replace IQ tests (Vaughn and Fuchs, 2003), while the historical necessity of categorising types of disabilities has been losing importance. A survey by Mooney, Owen and Statham (2008) found that categorising by disability is not the best way of collecting information for service planning. Indeed, specifications provided about intellectual disabilities are very often not relevant to the everyday practice of teachers and there is little convincing evidence that accurate diagnosis of conditions necessarily calls for syndrome-specific types of educational interventions (Kirk and Gallagher, 1979; Mittler, 2000; Vaughn and Fuchs, 2003). Although there is little doubt that many individuals with intellectual disabilities do have underlying neurological deficits, reliably identifying those deficits and using them to inform effective instructional programs has been an unsuccessful, problematic and unhelpful process (Chall, 2000; Mittler, 2002; Silver, 2001). There are many students whose difficulties in learning make it hard to place them clearly in one or other subgroup as this depends on where cut-offs between the subgroups are drawn (Norwhich and Lewis, 2001).

Such beliefs are reflected in the evolution of official classifications for SEN in the UK. The 1994 SEN Code of Practice (DfE, 1994) labelled learners with the following categories of needs:

- Mild, moderate, severe, profound and multiple learning difficulties: problems from acquiring basic literacy skills to learning basic self-help skills such as dressing and toileting;
- Specific learning difficulties: problems in acquiring basic literacy or numeracy skills;
- Speech and language difficulties;
- Emotional and behavioural difficulties;
- Physical disabilities;
- Hearing difficulties;
- Visual difficulties;
- Medical conditions: such as epilepsy or asthma, with associated SEN.

Advice given according to these categories presented more overlap than specificity (Mittler, 2000), and in 2001 attention was moved to how the context can support or hinder learning opportunities, no longer according to hard and fast categories, but within a wide spectrum of inter-related special educational needs (DfES, 2001). The terms learning difficulties and intellectual disabilities for example, usually refer to students with significantly sub-average achievement in learning (Wedell, 2003), but which may be accompanied by challenging behaviour, sight or hearing difficulties, autism, mental illness and many additional health problems (FPLD, 2007; Male, 1996; Mittler, 2002). Four broad areas replaced the previous categorisations: cognition and learning needs; behaviour, emotional and social development; communication and interaction; and sensory and/or physical. The present research is situated within the area of cognition and learning needs, in particular intellectual disabilities, which are still under-researched, probably due to the lack of diagnoses and specific descriptions of their difficulties and characteristics.

Intellectual disabilities

Terminology in the SEN field is not clear. Terms like mental deficiency, mental sub-normality, mental retardation, and mental handicap (Kwok, To and Sung, 2003) are no longer acceptable and have been replaced by learning disability, learning difficulty, intellectual impairment, intellectual disability (FPLD, 2007), developmental delay (Dockrell, Peacey and Lunt, 2002), individual needs and additional needs (Mittler, 2000). These terms are generally used for people whose capability to learn is affected, and therefore find it difficult to cope with everyday life, function independently in society and communicate with other people (FPLD, 2007). The term learning difficulties is commonly used in the UK to describe students with significantly sub-average achievement in learning (Wedell, 2003), and is generally well accepted by many of those to whom it has been applied (Abbott, 2007). The term intellectual disabilities has been standard in a number of countries (Mittler, 2002), and is the adopted terminology in this thesis.

Children with intellectual disabilities face challenging and life-long effects (Gerber, 2001), for which no organic cause and no accurate description of cognitive functioning may be known (Riley, 1989). Intellectual disabilities are not a disease, but a condition that involves many variables (Kirk and Gallagher, 1979). Individual children may have more than one type of need and for a significant majority of them there are no medical tests available (AuditCommission, 2002; Dockrell, Peacey and Lunt, 2002). Despite the lack of a precise definition, children with intellectual disabilities share key common characteristics in areas like perception and attention, social relationships, reasoning, abstraction and generalisation (Abbott, 2007; Stakes and Hornby, 2000).

To start with, perception and attention are fundamental abilities for interacting with the environment, by dealing with incoming stimuli. Perception can occur through visual, auditory, gustatory, haptic, kinaesthetic and olfactory means. When perceiving such variety of competing stimuli, the child must select what is relevant and bring it to the foreground of attention (Kirk and Gallagher, 1979; Vygotsky and Luria, 1993). This is what Vygotsky calls ‘artificial attention’ as opposed to the 'natural' kind of attention presented by an infant who, for example, turns his head away when submitted to strong luminosity (Vygotsky and Luria, 1993). Artificial attention is culturally rooted, and allows the perception of socially important stimuli that are intertwined with several other contextual factors, and thus harder to assimilate 'naturally'. According to Piaget, an object cannot be considered a perceptive stimulus if the perceiving organism is not affected by it (Piaget, 1967). Children with intellectual disabilities are often said to be distractible and off-task due to difficulties in forming such attentional strategies (Cawley and Parmar, 2001; Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000). Research has found that children with learning disabilities have a two to three years delay in their ability to selectively attend (Riley, 1989). Furthermore, they tend to use and heavily rely on external cues picked up from surroundings in order to respond to questions, which Scruggs and Mastropieri (1995) call 'outerdirectedness'. This may involve relying on the opinions and behaviours of others, and taking information from pictures or other objects in the surroundings regardless of their relevance. In other words, they struggle to weigh one idea against another, or to judge an idea according to some criteria, and do not readily recognise features relevant to the task in hand (Kirk and Gallagher, 1979; Scruggs and Mastropieri, 1995). The reluctance to use their own judgment and reasoning is a sign of these children's low self-esteem and low academic self-concept, accompanied by challenging behaviour as a way of avoiding failure. Predisposition to expect failure makes intellectually disabled children avoid social relationships, leading to problems in adjusting socially (Carlisle and Chang, 1996; Holden and Cooke, 2005; Kirk and Gallagher, 1979; Scruggs and Mastropieri, 1995).

Social relationships are also affected by the difficulties presented by these children in communicating ideas and feelings. The 'expressive domain' can be divided into two main categories: vocal and motor skills. In relation to the former, Vygotsky has shown the importance of language in the development of reasoning, and its strong connection with thought (Vygotsky, 1986). Language makes memory become more verbal and less visuopictorial, stimulates and reshapes thought, and becomes the most-used cultural tool (Vygotsky and Luria, 1993). Language has a functional role, which goes beyond communication: it represents the external world inside the person, and allows verbal planning, which is at the basis of human behaviour (Vygotsky and Luria, 1993). While a typical child is able to produce increasingly complex verbal messages with age, children with intellectual disabilities typically have delayed language acquisition. In general, deficits in speech and language, which can be due to a variety of reasons like hearing impairments, brain injuries, and intellectual disabilities, result in social, communication and learning problems (Kirk and Gallagher, 1979). Children with intellectual disabilities present difficulty in recalling particular words and phrases, communicating ideas and understanding the meaning of words. In practice, this leads to difficulty in understanding instructions, remembering what has been taught, and organising themselves (e.g. following a timetable, remembering books and equipment) (Cawley and Parmar, 2001; Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000). As to motor skills, they are not only means of performing physical tasks: they communicate feelings and ideas, but more than that, actions play a fundamental role for knowledge construction. According to Piaget, perception and action are not dissociable (Piaget, 1970). The importance of gestures for reasoning has been shown by a large body of research (Cook, 2007; Edwards, 2009; Goldin-Meadow, 2000), and the role of actions for learning is also advocated by the embodied cognition theory (Gallese and Lakoff, 2005), as discussed in Chapter 3. In spite of the fact that children with intellectual disabilities may have accompanying physical impairments, the present research does not focus on these, but on cognitive difficulties, taking into account the key role of actions.

Other key aspects when discussing intellectual disabilities refer to abstraction and generalisation. Generalisation is the ability to project acquired knowledge into other situations, including hypothetical ones, through reasoning and abstraction processes (Kirk and Gallagher, 1979). According to Vygotsky, a young child's thought is fully concrete: initially the child interprets each concrete instance as a unique, independent object. For example, a young child may know they have ten fingers in their hands, but not know how many fingers another person has. They cannot yet abstractly represent a quantity, quality or symbol – in other words they cannot extract from a concrete object a corresponding sign to be applied for a collection of objects in the same class (Vygotsky and Luria, 1993). A child's experiences allow the formation of increasingly complex associations between concepts that make them able to respond effectively to the environment (Kirk and Gallagher, 1979). As the child grows older, they learn cultural techniques to establish relationships and links to form knowledge. A child with intellectual disabilities does not form as complex concept organisations as the typically developing child's (Vygotsky and Luria, 1993), and people with intellectual disabilities may remain at the concrete stage for life. They present difficulty in reasoning in a logical manner, using processes like predicting and inferring, and they need concrete examples to slowly reach conceptual thinking. Their rate of cognitive development is slower, and reasoning for problem solving is less effective (Riley, 1989). They have difficulties in understanding and retaining abstract concepts, and in transferring and applying skills to different situations (Cawley and Parmar, 2001; Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000).

As a concluding note, according to Vygotsky, children with intellectual disabilities do not necessarily have defects in their natural functions, but they do not know how to make effective use of them (Vygotsky and Luria, 1993). For instance, an intellectually disabled child may have their sensory channels in perfect condition, and still be unable to select relevant stimuli from the environment. In a study on memory with intellectually disabled and talented children, Vygotsky showed that differences in task performance were due to difficulties that the first group had in using the cultural aids offered. In other words, both groups had similar results in experiments that measured natural memory, but intellectually disabled children performed much lower in experiments with cultural memory (i.e. with the use of external artefacts).

To sum up, four general themes emerge from the main characteristics of children with intellectual disabilities, namely: perception and attention; judgement and reasoning; social communication; and abstraction and generalisation. These characteristics provide a theoretical basis for qualitative analysis of evidences from the empirical studies (Chapter 8), regarding the relationships between aspects of tangible interaction and children's known learning difficulties.

The literature recommends some key general strategies for facilitating learning for children who present the difficulties discussed above (Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000), namely:

- Organising practical activities like games, simulations, role-plays and field trips;
- Using a VAK approach (visual, auditory, kinaesthetic) to utilise all the senses, with the aid of resource materials like visual aids, charts, physical artefacts and computers;
- Using practical, concrete, visual examples to illustrate explanations;
- Starting from what the child knows and going at their pace;
- Ensuring tasks are in the child's capability;
- Organising peer tutoring and cooperative learning groups;
- Focusing on oral language and social skills;
- Repeating, praising and encouraging, to build confidence;
- Keeping tasks short and varied.

Such strategies were considered in the design and methodology of the present research, detailed in Chapter 7. In general lines, a VAK approach was adopted through short, practical activities, simulations and concrete examples provided by the tangible technologies utilised. Based on the literature discussed here, it was assumed that such physical / sensory approach would help addressing the students' difficulties mentioned above (perception and attention; judgement and reasoning; social communication; and abstraction and generalisation). In addition to this, it was also hypothesised that the dynamics and interactivity provided by digital technology, when combined with physical representations, could improve even more the support to address such needs.

The context of schools

For mainstream schools, the new policies on SEN and inclusion implied extending the capacity of provision for children with a wide range of needs, developing teachers' skills, and adapting innovative approaches to achieve greater inclusion and overcome barriers to learning, including the provision of materials to improve access for disabled students (DfEE, 1997; DfES, 2004). Considering this scenario, schools and local authorities in the UK adopt various ways of dealing with children with special needs. The definition of disability from the Disability and Discrimination Act (1995) ("A person has a disability for the purposes of this Act if he has a physical or mental impairment which has a substantial and long-term adverse effect on his ability to carry out normal day-to-day activities." – Part 1, Paragraph 1) is used along with parent and carer definitions, medical diagnosis, and criteria related to the level of institutional service formally received (Mooney, Owen and Statham, 2008). At the end of the day, identification of learning disabilities largely relies on teachers' opinions (Vaughn and Fuchs, 2003). The present research aims to investigate innovative technological supports for the education of children that are said to have intellectual disabilities *from the point of view of their schools and teachers in their everyday practice*, rather than necessarily being formally labelled by medical diagnoses, measurements of neurological deficits, or formal statements of special needs. The goal is to address the context of schools and the needs of children and teachers as they come up in their routine activities, rather than focusing on syndrome-specific interventions at a more theoretical level.

In primary and secondary schools in the UK, the incidence of students with SEN without statements is greater for boys (around one in every five boys) than it is for girls (around one in every seven girls) (DCSF, 2008). Similarly the incidence of students with statements of SEN is much higher for boys. In 2004, 68% of children attending special schools in England were boys (DfES, 2004). In January 2008, 92,000 boys in primary and secondary schools had statements of SEN (around one in every forty boys) compared with 34,400 girls (less than one in every hundred girls) (DCSF, 2008). The sample of the present research, which consisted of school groups with intellectual disabilities, reflected the tendency pointed by such figures. Considering all groups that agreed to participate, there were twice as many boys as girls. The sample was thus consistent with the predominance of males in schools.

The rate of incidence of students with SEN without statements in primary and secondary schools peaks at ages 8 and 9 (DCSF, 2008), with only a small drop for ages 7 and 10 (Figure 2.1). Mooney, Owen and Statham (2008) found that children under five years are less likely to be known as disabled (only 8% of disabled children in this survey were 0-4 years old). It may be that some disabilities develop or only become apparent with age, but also children in preschool age are not in the data collected by SEN reports.

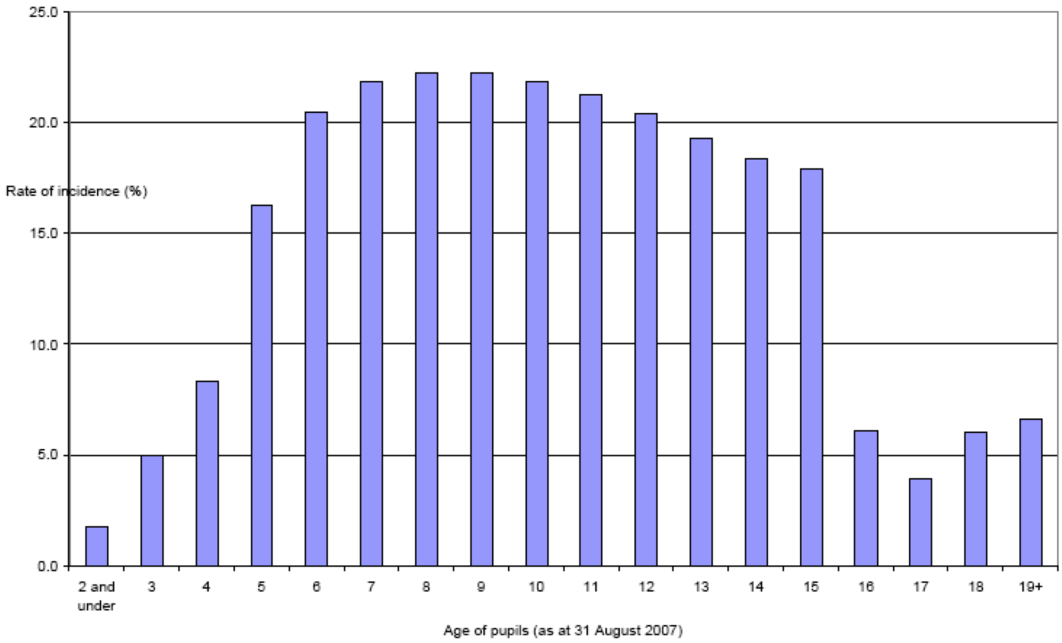


Figure 2.1: Age of students with SEN but without statements
Source: Statistical First Release - Special Educational Needs in England (DCSF, 2008)

In January 2000, 90.4% of children with statements in England were aged between 5 and 15. There were just over 10,000 (3.7%) aged under 5 and nearly 16,500 (5.9%) aged between 16 and 19 (DfEE, 2000). In 2002, the percentage of students with statements in England increased from nursery (1.3%), through primary (1.7%) to secondary (2.5%) (Dockrell, Peacey and Lunt, 2002). The rate of incidence of students with statements of SEN in primary and secondary schools peaks when students are aged 14 at around one in every 40 students (Figure 2.2). At the end of the first year of secondary school, around a third of students perform worse in tests than they did a year earlier. Boys show less progress than girls and are more likely to become disaffected in years 7 and 8 (Blunkett, 2000). At 14 – 16 years, many SEN young people become seriously disengaged with learning and leave school with few or no qualifications (DfES, 2004).

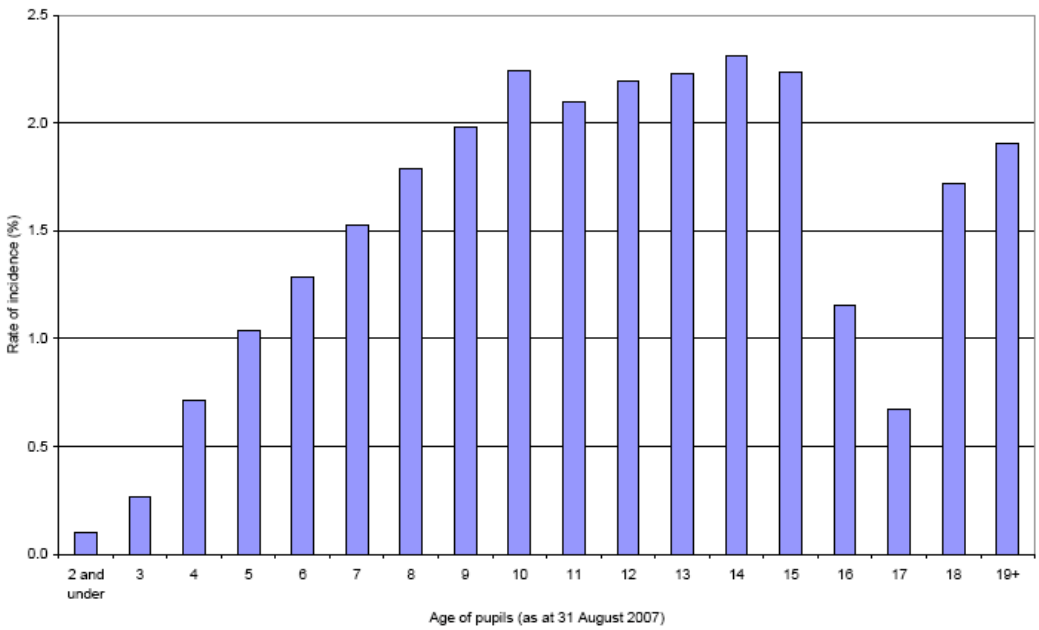


Figure 2.2: Age of students with statements
Source: Statistical First Release - Special Educational Needs in England (DCSF, 2008)

The age range of the participants was chosen according to the evidences of disengagement in the transition from primary to secondary school, in order to try to help decreasing the difficulties faced by these students. With few exceptions, participants in this research were in the end of primary or beginning of secondary school, with ages ranging mainly from 11 to 13 years.

Implications

In the present work, the term intellectual disabilities is adopted to refer to the condition of children whom this research aims to address. The term was chosen for more than one reason. First of all, it is standard in many countries and commonly used in educational contexts (Mittler, 2002). Secondly, within the range of special educational needs, it conveys a focus on cognitive difficulties rather than physical disabilities, as is the scope of this work. Last but not least, it does not restrict the population considered to any specific syndrome or disability, and does not imply a detailed categorisation or labelling of special educational needs. Such holistic view, as opposed to fast and hard categories of needs, is aligned with recent recommendations from government codes of practice (DfES, 2001), and with historical (Mittler, 2002) and empirical research (Mooney, Owen and Statham, 2008), and backed up by the little evidence of the actual benefits of syndrome-specific types of educational interventions (Mittler, 2000). The term encompasses all children identified *in their schools* as having cognitive difficulty that leads to underachievement.

Taking a socio-constructionist perspective, in the present work intellectual disabilities are seen as outcomes of the interaction between the characteristics of the child and the resources and deficiencies of the environment (Abbott, 2007; Wedell, 1990). It is important to note that socio-constructionist perspectives encompass the various factors of the environment such as physical settings, communication between students and with teachers, type of instruction delivered, motivation and feedback for the student. However, due to limitations in scope, the present research focuses on the mediation of students' interaction with the environment by specific tools and how these artefacts can help addressing these students' difficulties. It is true that such limitation risks taking insufficient account of the social and cultural contexts which support the technology use, as pointed by Abbott (2007); nevertheless a choice had to be made as to which aspects of the complex interactions that take place during learning processes were to be analysed in detail. The present research does not aim to evaluate the efficacy of particular hardware or software, thus becoming 'technologically determinist' (Abbott, 2007), but to analyse which aspects of a new paradigm of technology may be particularly beneficial for children with intellectual disabilities.

The socio-constructionist perspective is also at the root of moves towards inclusion in schools (Thomas and Loxley, 2007), which is heavily supported by governmental plans (DfES, 2004). The placement of children with intellectual disabilities in mainstream schools and classrooms makes the attempt to deliver specific types of instruction, according to each supposed 'category' of special needs, an even bigger challenge. Except for children who require specific accessibility solutions to overcome physical deficiencies, in mainstream schools children with intellectual disabilities are mostly treated as a group that might receive extra-class support, as confirmed by the field research (Chapter 6). In other words, schools have no practical means for giving specific provision for each different syndrome or category of special needs. The present work aims to address such reality, backed up by the socio-constructionist perspective. Thus, participants were chosen according to their school's criteria and decision for placing them in a group of children with difficulties to learn. It is not in the scope of the present research to discuss the methods and criteria used in schools for identifying intellectual disabilities, or to identify the causes of such disabilities and classify them as having medical, social or economical origins – it was a premise of the present work that children that contributed to this research were selected on the basis of being considered intellectually disabled *by their schools* (such selection criteria has been adopted in other research on learning disabilities e.g. (Butler et al., 2003; Riley, 1989; Virnes, Sutinen and Kärnä-Lin, 2008)). It is important to note that it is mostly in the school environment that children with learning difficulties are defined as such, and this directly affects their role in the scholar group, their attitude, performance and outlook on themselves (Khamis, 2009; Wedell, 2003). To sum up, the aim here is to investigate how new technological interventions can contribute to the educational process of students labelled as intellectually disabled in their schools.

Children who participated in this study formed a sample with key common difficulties that corresponded to those mentioned in the literature, i.e. in the areas of perception and attention; judgement and reasoning; social communication; and abstraction and generalisation. They were in the end of primary or beginning of secondary school, with ages ranging mainly from 11 to 14 years, with few exceptions. This age range was chosen for corresponding to the problematic transition from primary to secondary school bringing frustration and disengagement for SEN students, and often making them leave school around 14 years of age (Blunkett, 2000; DfES, 2004; Dockrell, Peacey and Lunt, 2002). The predominance of boys with SEN found in schools (DCSF, 2008; DfES, 2004; Mooney, Owen and Statham, 2008) and also consistently reported by various researchers throughout the years as pointed by Male (1996) was also reflected in the sample (31 boys and 15 girls).

Chapter 3 – Theoretical foundations for learning

Learning perspectives are often based on metaphors of mind. Cognitivist views predominantly model the mind as an information processing system, where knowledge is *information* and intelligence is its *processing*. These theories view the individual separately from the environment, and learning as a process of perceiving, recording, storing, retrieving and reapplying information (Ackermann, 1998; Wheatley, 1991). Behaviourist models of learning are based on such 'computer metaphor' of the mind. On the other hand, socio-constructionism and constructivism consider knowledge as *experience*, actively constructed through interaction with the environment. Knowledge, according to these theories, is not 'out there' ready to be acquired, but is constructed through a process of selecting, consolidating and reorganising experience, keeping a balance between stability and change, or, in Piagetian terms, between assimilation and accommodation (Ackermann, 1998).

Early cognitivist approaches tended to give very partial accounts of the relationship between context and cognition (Daniels, 2001), and Piaget's constructivism has also been criticised for its focus on the individual and personal characteristics. The Vygotskyan sociocultural perspective, with its strong emphasis on the role of the environment, has provided the basis for theories of situated and distributed learning, where knowledge is highly context-dependent (Ackermann, 1998; Daniels, 2001). According to situated cognition, people rely on external supports to make their ideas tangible and shareable. In this sense, sophisticated thinking depends on successfully dealing with external representations, or 'objects-to-think-with' (Papert, 1980).

This chapter presents the key ideas that form the theoretical argument of the present research, in terms of learning processes. Firstly, the importance of physical interaction is introduced as part of the constructivist, embodied argument for learning through action and discovery. Secondly, the role of external representations within such process is discussed in terms of tool mediation. The chapter ends by relating such theoretical concepts to the field of intellectual disabilities.

Learning by doing

Despite the so-called 'constructivist revolution', many school practices still reflect behaviourist assumptions based on memorising facts and practicing algorithmic procedures, with reinforcement of correct answers and extinction of wrong ones (Wheatley, 1991). Instruction is mostly based on textbooks, teacher lectures and demonstrations, with students being passive rather than active learners (Cawley, 1994). This is known as 'learning by imposition' (Bishop, 1985), which more often than not can become meaningless for the learner. Based on a constructivist perspective, the present work argues that school learning should be about sense making, closer to what people experience outside of formal school settings, particularly through activity performed on objects (Wheatley, 1991). Knowledge is thus viewed as contextual and not disembodied, intimately related to the action and experience of the learner and never separated from them (Wheatley, 1991), as discussed in this section.

The importance of physical interaction

There is a long debate in scientific research about the relationship between body and mind (Damasio, 2003). The dualist perspective, disseminated by Descartes in the seventeenth century, sees the mind as non-physical substance, purely intellectual and cognitive (*res cogitans*), and the body as corporeal substance (*res extensa*). Despite classifying body and mind as substances of completely different nature, separated and therefore not in contact, Descartes believed that they had influence upon each other, exclusively through the pineal gland. Modern neurobiology has shown that mental phenomena are strongly related to cerebral circuits, and caused many to abandon Descartes' dualist perspective (Damasio, 2003). However, this does not mean that the matter was resolved – the role of the body for the mind's formation is still not clearly explained. Damasio suggests a change of perspective to see the mind as emerging from the brain, which is situated in the body and interacts with it. The mind thus emerges from biological tissue of nervous cells that share characteristics of other living tissues of the body (Damasio, 2003). For Damasio, brain activity regulates the body physically and socially, and such regulatory operations depend on the creation and manipulation of mental images (ideas and thoughts) - a process called *mind*. Perception of objects and situations, and response to stimuli, depend on images, which can be visual, auditory, tactile, olfactory and gustatory, and the *mind* cannot perceive anything unless it is through the *body* (Damasio, 2003). The brain is responsible for vision, motion, spatial understanding, interpersonal interaction, coordination, emotions, language and everyday reasoning. Human concepts and language are limited by the structure of the brain, the body and the world, and all conceptualisation, knowledge and thought make use of the physical neural structure of the brain (Lakoff and Núñez, 2000). Ideas that come to people's minds originate in corporeal structures in a specific state and determined circumstance, in interaction with the environment (Damasio, 2003). All abstract concepts and principles originate in bodily experiences and their metaphorical projections into abstract domains (Johnson, 1987). It is therefore possible to talk about an 'embodied mind', meaning that the nature of the body and human functioning in the world structure both human concepts and human reason (Lakoff and Núñez, 2000). A large body of research advocates that human interaction with the environment, through the body and physical activity, shapes cognitive structures and thus bodily activity should not be divorced from the perception of meaning (Anderson, 2003; Edwards, 2009; Gallese and Lakoff, 2005). From the point of view of phenomenology, Heidegger views cognition as *praxis*: people have primary access to the world through practical involvement (Winograd and Flores, 2004); and Merleau-Ponty argues that perception and representation always occur in the context of, and are structured by, the *embodied agent* in the course of its engagement with the world – representations are thus formed through bodily experience, and not given content or form by an autonomous mind (Hilditch, 1995). In phenomenology, it is only through actions that humans can find the physical and social manifestations of the world meaningful (Dourish, 2001). In conclusion, mind, brain and body are inseparable parts of a normally functioning organism (Damasio, 2003) and perceptual and motor systems play a foundational role in concept definition and in rational inference (Lakoff and Johnson, 1999).

Despite the fact that the dualist perspective has not been the prevalent scientific view for many years now, in educational practice thinking is still often regarded as something cut off from experience, and capable of being realised in isolation, while bodily activity is still predominantly seen as distraction, unrelated to mental activity, and to be suppressed. In other words, bodily action and experience are linked to a 'mere' material world and separated from 'thinking', a higher faculty that grasps meanings through 'spiritual' activity (Dewey, 2001). For the sake of keeping discipline, physical quietude and rigid uniformity of posture and movement are praised and rewarded in classrooms. In such contexts, students listen, read, and reproduce what is told and read (Dewey, 2001). In the light of these pedagogical approaches, it is believed that the mind can grasp connections and relationships only by paying attention, without experience. In this sense, for a long time the dominant theory of learning was based on acquisition (Sfard, 1998), with children seen as recipients to be passively filled with knowledge and competences by teachers.

However, students' lives, as with all other persons, consist of active contact with things and people, and it is only in such experiences in the physical world that theory has vital and verifiable significance (Dewey, 2001). Most 'real-world' thinking is employed for practical ends, and exploits the possibility of interaction with, and manipulation of, external props (Anderson, 2003). According to Dewey, children learn in consequence of their direct activities, and not because they are told that they have to learn something, and so make their attitude self-conscious and constrained (Dewey, 2001). Vygotsky argues that when concepts are taught through pure transfer of verbal statements, the child may assimilate the words but will not understand the meanings, and will not be able to consciously employ the underlying concepts in any other situation, because they have acquired 'empty knowledge' – they may recite the words, but do not understand their true meanings (Vygotsky, 1986). Vygotsky cites Tolstói who says that "to deliberately transfer new concepts to the student is, I am convinced, as impossible and useless as teaching a child to walk according to the laws of balance. Any attempt in this direction only deviates the students from the proposed aim, like the brutal force of a man who, trying to help a flower to bloom, uncoils its petals" (Tolstói, 1903, p. 146). According to Dewey (2001), "there is no such thing as genuine knowledge and fruitful understanding except as the offspring of doing" (2001, p. 283). Cognition is thus a highly embodied activity, and *thinking* beings should therefore be considered first and foremost as *acting* beings (Anderson, 2003).

Increasingly, educators are highlighting the importance of embodied learning activities promoted by bodily experiences or interactions with the world (Rambusch and Ziemke, 2005). For example, research has shown the importance of physical gestures in problem solving (Cook, 2007; Edwards, 2009; Goldin-Meadow, 2000; Manches, O'Malley and Benford, 2009). In this line of thought, body movements, the ability to touch, feel, manipulate and build sensory awareness of relationships in the world are considered crucial to children's cognitive development (Healy, 1998). The present research is framed within an embodied cognition theoretical foundation, making the case for learning through practical experience as opposed to passive acquisition, engaging the sensory-motor system through physical interaction with tangible technologies.

Constructing knowledge through action

The views presented in the previous section are connected with the idea of education taking place through 'construction' rather than through the traditional 'tell and be told' teaching-learning process (Dewey, 2001; Wheatley, 1991). This approach is part of the so-called 'constructivist revolution' (Mayer, 2004), which brought new conceptions of learning and teaching since the pioneer work of Piaget (Piaget and Inhelder, 1969). According to Piaget, in learning processes children are actively involved in the construction of meanings and understanding of concepts for themselves, having as starting point their personal previous knowledge, which is to be developed and reinterpreted to form new knowledge (Piaget, 1967). Knowing consists on acting on the environment and transforming it, and perception is only meaningful when connected to action. It is not possible to know the properties of an object if not acting upon it, and cognitive development implies the capability of coordinating actions in increasingly complex ways (Piaget, 1967). Meanings are not to be 'sent' to students' heads – instead, each student builds their own meanings, producing viable, embodied and contextual explanations of their experiences: "to know is to act" (Wheatley, 1991, p. 10). As Dewey puts it, “education is a constant reorganizing or reconstructing of experience” (2001, p. 81).

It is clear in Piaget’s constructivism, as in embodied cognition theories, that direct physical interaction with the world is a key component of children’s cognitive development (Piaget, 1970). For Piaget, the first stage of development is the sensory-motor stage, when infants are centred on their own bodies, and do not see themselves as subjects acting on objects of the environment. Experimenting through actions eventually makes them able to coordinate their actions as means to reach a goal. When reaching the pre-operational stage, typically around two years old, the child is able to internalise and conceptualise actions, through symbolic representations like language and mental imagery. In other words, the child starts to learn symbols and to understand them as representations of something else (Piaget, 1970). Around seven years old, children reach the stage of concrete operations, when they are able to logically think about an object, when manipulating it. In other words, children are able to imagine different scenarios and situations about the objects, performing reversible mental actions and dealing with the concept of ‘conservation’, but they still think in terms of the concrete instances they have access to. Around eleven years old, children reach the stage of formal operations, when they are able to logically use symbols related to abstract concepts, like algebra and science. They can think about multiple variables in systematic ways, formulate hypotheses, and consider possibilities. The capability for abstraction permits children to reason beyond the ‘concrete reality’ available for them at a specific moment in time, and to operate logically on symbols and information that do not necessarily refer to objects and events of the physical world (Piaget, 1970).

The definition of Piaget’s formal operations stage reveals a key difference between constructivism and embodied cognition regarding the concrete-abstract relationship. Piaget theorised that children must first construct knowledge through concrete operations (with physical materials) before moving on to formal / abstract operations (Piaget, 1970). For Piaget, ideally, as children grow older and develop, they gradually become independent from what Bruner calls ‘enactive’ representations (Bruner, 1960), reflecting a progression from concrete to abstract. However, Bruner's modes of representation (enactive, iconic and symbolic) were not defined as neat age-related stages as in Piagetian theory. In fact, Bruner suggests that the cycle of 'enactive - iconic - symbolic' representations can take place at any age, including adult, when the learner is presented to new material (Bruner, 1960). Bruner's ideas thus relate to embodied cognition theories, which advocate that concrete experiences from childhood are not solely a starting point for abstract thinking as Piaget argues, but become embodied in higher order thinking (Lakoff and Johnson, 1999). Adult thinking is thus grounded in prior perceptual experiences, and there is no such clear cut between concrete and abstract phases, or (concrete) perceptual experiences and (abstract) cognition. It is not in the scope of the present research to discuss divergences between Piaget, Bruner and embodied cognition views or prove one of them right. What the present work does is to incorporate Piaget's views on the importance of actions and physical experience in the learning process into the frame of embodied cognition. In this sense, both theories are complementary and not contradictory, and help building a solid theoretical foundation for proposing the use of tangible technologies for learning.

Learning through discovery

Constructivism has given rise to various 'self-guided' pedagogical approaches whose effectiveness has been largely discussed (Alfieri et al., 2011; Kirschner, Sweller and Clark, 2006). Such approaches, all of which emphasise exploration, discovery and invention, include: discovery learning (Bruner, 1961), problem-based learning (Schmidt, 1983), inquiry learning (Rutherford, 1964), and experiential learning (Kolb, 1984). Common to all of them is the idea that learners draw on their own experience and prior knowledge to interact with the environment by exploring and manipulating artefacts, performing experiments, exploring phenomena, and attempting to apply principles (Alfieri et al., 2011; Kirschner, Sweller and Clark, 2006). In particular, discovery learning is characterised by not providing the target information or conceptual understanding to the learner, who must find it independently, conducting investigations with the provided materials (Alfieri et al., 2011; Bruner, 1961). Bruner suggests that students are more likely to remember concepts if they discover them on their own than if they are taught directly (Bruner, 1961).

However, despite its roots in the constructivist theory and modern pedagogical approaches, discovery learning has not escaped a fair amount of criticism. On the one hand, it is advocated that when learners must discover or construct essential concepts for themselves, in information-rich settings, they are given opportunities to notice patterns, discover underlying causalities, and learn in ways that are seemingly more effective and robust (Alfieri et al., 2011; Kirschner, Sweller and Clark, 2006). On the other hand, there is a worry that students left to self-discovery of topics can be led to errors, misconceptions, negligence of important school competences, or be confused and frustrated (Alfieri et al., 2011; Kozulin, 2003). A large body of research has failed to prove the pedagogical benefits of discovery learning approaches over direct instruction (Kirschner, Sweller and Clark, 2006; Mayer, 2004). Based on a literature review on the topic, Mayer (2004) emphasised that although constructivist-based approaches might be beneficial for learning under some circumstances, unassisted discovery learning does not seem advantageous because of its lack of structure. As a matter of fact, opportunities for constructive learning might not present themselves when learners are left totally unassisted (Alfieri et al., 2011), and pure discovery can be ineffective as there is a high risk that students do not come into contact with the to-be-learned principle and therefore have nothing to integrate with their knowledge base (Mayer, 2004). There are also concerns that the lack of structure of discovery learning may overwhelm the learner's cognitive workspace (Alfieri et al., 2011). On the other hand, direct instruction methods can be ineffective when they discourage learners from actively making sense of the presented material (Mayer, 2004). Despite seeming reasonable to expect learners to be able to construct their own understandings with minimal assistance because they do so in the context of everyday activities, the content and context of formal education require more assistance to make learners reach accurate concepts, understandings and solutions (Sweller, Kirschner and Clark, 2007). It is also important to note that people often learn what they do in their daily life activities through forms of guided participation (Rogoff, 1990). In schools, the amount of mediation given by the teachers is usually inversely proportional to the level of structure of the tasks and materials (Kozulin, 2003).

In order to address the problematic lack of structure while still keeping the pedagogical benefits of the constructivist approach, the so-called ‘enhanced-discovery methods’ or ‘guided discovery’ propose the integration of techniques like feedback and scaffolding (Rosenshine, 2009) to introduce a certain degree of guidance in discovery learning tasks. This should help to reach the ideal envisioned by Bruner in his discovery learning theory (Bruner, 1961): students need enough freedom to become cognitively active in the process of sense making, and enough guidance so that they construct useful knowledge (Mayer, 2004).

Alfieri et al. (2011) systematically compared enhanced discovery-learning methods (generation, guided discovery and elicited self-explanation), with a variety of instructional conditions, including unassisted discovery and explicit instruction. Generation consists of having learners generate rules, strategies, images, or answers to experimenters’ questions. Elicited explanation consists of asking learners to explain some aspect of the target task or target material, either to themselves or to the experimenters. Finally, the guided discovery method consists of either some form of instructional guidance (scaffolding) or regular feedback to assist the learner at each stage of the learning tasks (Alfieri et al., 2011). The meta-analysis indicated that while more explicit-instructional tasks were found to be superior to unassisted-discovery tasks, better results were obtained for enhanced discovery instructional methods over direct instruction. This backs up the superiority of the method of guided discovery over pure discovery described in Shulman and Keisler’s book (1966). In particular, in support of constructivist claims, the construction of explanations (in the case of the elicited self-explanation method) and the participation in guided discovery were found to be better for learners than being provided with an explanation or explicitly taught how to succeed on a task (Alfieri et al., 2011). Overall, Alfieri et al. (2011) concluded that enhanced-discovery approaches requiring learners to be actively engaged and constructive seem optimal, and as such should include at least one of the following: (a) guided tasks with scaffolding; (b) tasks requiring learners to explain their own ideas and providing feedback on these ideas; or (c) tasks that provide worked examples of how to succeed in the task.

Alfieri et al. (2011) suggest that the debate on issues of unassisted forms of discovery should move towards a discussion of, among other topics, how scaffolding is best implemented and how to provide feedback. In this sense, Dewey argues that rather than ready-made, specific solutions, material offered to the student should be adaptable to different contexts, allowing the child to be a discoverer (Dewey, 2001). According to Martin and Schwartz (2005), it is not the representation per se that leads to learning but rather the process of transforming and interpreting the configuration of the representations. The authors propose that the emergence of new interpretations through physical adaptations of the environment can be an important benefit of physical action for learning abstract ideas (Martin and Schwartz, 2005). In many cases, however, the manipulation of the materials alone does not provide sufficient feedback (Alfieri et al., 2011). The challenge of teaching by guided discovery is to know how much and what kind of guidance to provide and to know how to specify the desired outcome of learning (Mayer, 2004).

In this direction, Chi (2009) and Mayer (2004) discuss the differences between learning tasks that require the learner to be merely active and learning tasks that require the learner to be constructive. The idea that constructivist learning requires active teaching methods is a recurring theme in the field of education (Mayer, 2004). According to Dewey (2001), thought or reflection is the discernment of the relation between what one tries to do and what happens in consequence, and every meaningful experience has some element of thought. The stimulus for reflection is the wish for determining the meaning of an act, performed or to be performed. Dewey argues that individuals must try, in play or work, to do something with material according to their own impulsive activity, and then note the interaction of their energy and that of the material employed. Nevertheless, Chi (2009) argues that although hands-on activities have a greater level of engagement than passive reception of information, this does not necessarily mean that learners will be able to make sense of the materials for themselves. From Chi's perspective, truly constructivist learning activities should be designed so that learners not only engage in the learning task (e.g., by manipulating objects) but also construct ideas that surpass the presented information (e.g. elaborating, predicting, reflecting) (Chi, 2009). To be constructive, an activity must produce outputs that go beyond and are not explicitly presented in the learning materials, otherwise it is not constructive, but merely active. Thus, in order to know whether a learner is actually generating new ideas in a constructive activity, the content of the outputs must be analysed. For example, self-explanations that are nonsensical, irrelevant, or verbatim utterances, do not constitute a constructive activity – for this, they must be meaningful elaborations that go beyond what was presented (Chi, 2009).

The present research builds on the advantages of discovery learning, and adopts tangible technologies as learning materials to provide a potentially fruitful environment for discovery through physical interaction. But beyond that, the interactivity and dynamics of the digital representations are powerful means of giving learners feedback and scaffolding in some form of guided discovery, and helping to overcome the problematic lack of structure of such exploratory approaches.

The role of external representations

As aforementioned, discovery learning and similar pedagogical approaches rely on the exploration of external representations by students, as the core of the discovery learning process. It is a human characteristic to exploit the environment in order to extend cognitive capabilities, through a variety of strategies, tools and representations, which, broadly speaking, is called 'external cognition' (Scaife and Rogers, 2005). Such representations are seen by Bruner as 'cognitive amplifiers', i.e. culturally invented technologies that serve to amplify basic human capabilities (Bruner, 1974).

While the field of *embodied* cognition highlights the role of perceptual experiences in conceptual development, *external* cognition focuses on the interaction between cognition (internal representations) and external representations (Manches and Price, 2011). In other words, external cognition combines cognition with perception and manipulation of external representations. Zhang argues that external representations are not simply inputs and stimuli to the internal mind, but are intrinsic to many cognitive tasks, guiding, constraining, and determining cognitive behaviour (Zhang, 1997). Zhang's view is aligned with *distributed* cognition, which discusses how cognitive activity is distributed in human minds, external artefacts and groups of people, across space and time (Hutchins, 1995; Norman, 1988). According to Salomon, information is processed between individuals and tools and artefacts provided by culture (Salomon, 1993). A distributed cognitive task is thus neither solely internal nor solely external, but a system of distributed internal and external representations (Zhang, 1997). Problem solving is therefore constrained both by the complexity of the environment and by the limitations of the mind. For example, while the environment can be complex because of the high amount of information, real time requirements, and unpredictable outcomes, the mind has limited capacity of information processing, working memory and attention. Thus, tasks of learning, remembering, and transmitting knowledge are distributed, and cognitive tasks that exceed individual abilities are shaped by a social organisation of distributed cognition (Hutchins, 1995).

External representations can be as varied as objects, physical symbols, pictures, graphs, external rules, relations embedded in physical configurations (e.g. spatial layout of diagrams), and other information-holders that can be captured from the environment and processed by the perceptual systems (Zhang, 1997). Extensive research shows how external representations are used in many cognitive tasks like reasoning, decision-making and problem solving (Zhang, 1997). In particular, research has demonstrated how manipulating external representations can reduce cognitive effort in problem solving, through 'computational offloading' (Scaife and Rogers, 2005; Zhang, 1997).

Symbolic mediation

External representations act as symbolic tools that mediate human activity and cognition. For example, a knot on a handkerchief to remember something, and a grocery-shopping list, are basic symbolic mediators that help organising cognitive functions. It is important to note, however, that the notion of symbolic mediation is not limited to environmental resources, but also applies to *internalised* representations, like higher-level symbolic systems such as language itself (Kozulin, 2003). Human beings interact with the world through mediating means such as complex systems of objects and structures, both material and immaterial (Kaptelinin, 2013). People function in material environments with the mediation of physical-cultural tools and cultural-material systems of words, signs and other symbolic values (Lemke, 1997).

For Vygotsky, the nature of human mental processes is determined by mediation. Vygotsky's primary focus is on *sign mediation*, emerging in the external world and being translated internally, and the accompanying transformation of mental functions. Vygotsky's disciple Leontiev chose to focus on *tool mediation*, and the corresponding transformation of human meaningful and purposeful activities (whose components can be internalised and transform mental processes). Leontiev pays special attention to tools as mediators of object-oriented activities (Kaptelinin, 2013). Kaptelinin suggests that actions with tools as physical artefacts can cause the internalisation of signs; and sign mediation of mental operations may affect the use of physical tools by making human actions independent from their immediate situations. In other words, human tools are, as a matter of fact, combinations of tools and signs (Kaptelinin, 2013). According to Lemke, 'things' contribute to solutions as much as 'minds': information and meaning are coded in the configuration of objects and environmental options, as well as in verbal routines and 'mental' operations (Lemke, 1997).

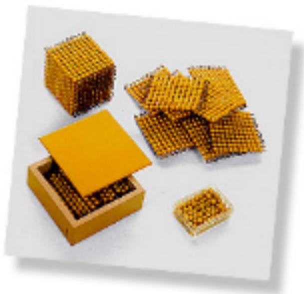
The focus of the present work is not on the internalisation of signs, but rather on how the characteristics of specific external symbolic representations (in the form of tangible interfaces) can support children with intellectual disabilities in processes of discovery learning, serving as mediating tools for conceptual exploration.

Educational manipulatives

In the context of symbolic, external representations that mediate learning, associated with physical engagement, educational manipulatives represent a long tradition that became very popular in constructivist schools (Moyer, 2001; Stacey et al., 2001). Overall, manipulatives are external representations that act as symbolic mediators in the process of generating metaphors and predictions and of transferring concepts across different contexts. They are not simple 'instruments' meant to reach a goal, such as a knife, designed to cut. Instead, they are symbolic representations of concepts, which work as 'signs' that mediate thinking.

Long before Piaget's constructivist theory was published, the educator Johann H. Pestalozzi (1746-1827) had already asserted the need to learn through senses and physical activity. Pestalozzi was one of the first advocates for hands-on learning, arguing for 'things before words, concrete before abstract' (Resnick et al., 1998). Other educators with similar beliefs followed Pestalozzi throughout the years: Friedrich Froebel with the world's first kindergarten in 1837 filled with the Froebel's gifts (Figure 3.1, left) (Brosterman, 1997); Maria Montessori, whose work and materials like the golden beads (Figure 3.1, centre) inspired a network of schools in which manipulative materials play a central role (Montessori, 1912); Zoltan Dienes, whose Dienes' blocks became one of the most popular manipulatives; and Georges Cuisinaire, who created rods to convey concepts of fractions (Figure 3.1, right).

Froebel's gifts
Source:
www.visitkinderhaustoys.com



Montessori golden beads
Source: www.ehow.com

Cuisinaire rods
Source:
https://eee.uci.edu/wiki

Figure 3.1: Examples of traditional manipulatives

These materials explore patterns, forms, colours and other physical characteristics capitalising on children's sensory capabilities. The possibility of touching and moving materials around creates enjoyable hands-on experiences that help to keep children's focus of attention (Halford and Boulton-Lewis, 1992; Hynes, 1986; McNeil and Jarvin, 2007; Mix, 2010). But more importantly, advocates of manipulatives say that the materials play a key role in enabling children to explore concepts through direct physical manipulation of objects (which also is believed to improve children's memory), and in helping children to understand the application of abstract ideas to real-life situations (Eisenberg, 2003; Marzola, 1987; McNeil and Jarvin, 2007; Resnick et al., 1998). Such views relate to embodied cognition beliefs that students' abstract thinking is closely anchored in their concrete perceptions of the world (Thompson, 1992), and thus actively manipulating physical materials allows learners to develop a repertoire of images that can be used in the mental manipulation of abstract concepts (Martin and Schwartz, 2005; Moyer, 2001). This is consistent with Bruner's ideas on allowing children to experience a variety of concrete objects to make them infer abstract principles embodied in the perceptual properties of the individual objects (Bruner, 1966).

Research on manipulatives has shown that children can solve problems and perform in symbolic manipulation tasks with physical objects when they fail to perform using more abstract representations (O'Malley and Fraser, 2004). Concrete representations are easier to talk about, to describe and to analyse than language-based solutions: it is easier to describe physical actions on physical objects than to describe operations on symbols (Hall, 1998). However, according to Ball (1992) and O'Malley and Fraser (2004), the main point is not that the objects are easier to understand, but that kinaesthetic experience enhances perception and thinking, and physical activity itself helps to make abstract concepts more accessible by building representational mappings that serve to underpin more symbolically mediated activity.

However, mappings between physical objects and underlying abstract concepts are not always transparent to students, and the objects alone may not be sufficient for supporting students in their understanding of symbolic representations of abstract ideas – manipulatives are not, of themselves, carriers of meaning and insight (Ball, 1992; Goldstone and Son, 2005; Kozulin, 2003). There is a long debate in the literature about the real benefits of manipulatives (Clements, 1999; Goldstone and Son, 2005; Hall, 1998; Kaminski, Sloutsky and Heckler, 2006; McNeil and Jarvin, 2007; Uttal, Scudder and DeLoache, 1997). In some cases, symbols can become useless if they do not have their meanings as cognitive tools properly presented to the child, and simple availability may not be sufficient. According to Kamii, Lewis and Kirkland

(2001), manipulatives are useful if they encourage the process of thinking in problem solving situations. For instance, Hiebert found that students have difficulties with fractions because they fail to connect the 'form' (i.e. the symbols that represent them) with 'understanding' (i.e. real-world situations related to fractions) (Hiebert, 1985). According to Clements (1999), the emphasis on the use of physical materials as mediators for learning results from a general belief that learning should be made 'concrete', but the real benefits of pedagogical materials lie mainly in their effectiveness to connect concepts to the real world, and not simply in their physicality. It cannot be assumed that children learn abstract concepts simply by touching and moving these objects (Kamii, Lewis and Kirkland, 2001).

Digital technologies as mediators

Digital technologies, like other technologies, were created by humans as their own projections and extensions, and according to the mediational perspective, are considered means through which human beings act in the world, and that affect and shape the structure, functioning, and development of human mind and action, having a direct impact on human perception, action, cognition, emotions, and communication (Kaptelinin, 2013). Norman proposed that digital technologies serve as *cognitive artefacts* that can augment human cognition (Norman, 1991) and Pea agreed that technological tools 'expand' intelligence (Pea, 1993). In 1954, Heidegger considered that the new technology of that time (machine-powered) revealed the world differently, when compared to traditional ones (Heidegger, 1993), and in 1986 Winograd and Flores considered computers "radical innovations that opened up whole domains of possibilities for the network of human interactions" (Winograd and Flores, 2004, p. 6), creating "new ways of being that previously did not exist and a framework for actions that would not previously make sense" (p. 177). The Russian psychologist Tikhomirov argued that computers are a qualitatively new kind of mediator that reorganise the ways that humans know (Tikhomirov, 1981). Nowadays, the ubiquitous computing paradigm, with wearable, mobile and tangible artefacts, embeds technologies in a much wider range of contexts and tasks (Borba and Villareal, 2005). According to the mediational perspective, technologies do not have, per se, an automatic effect of 'amplifying' human minds. The influence of digital technology on human mental processes depends on its integration as mediator into meaningful activities and the context of people's social relations, within the network of equipment and practice where people and technologies are situated (Kaptelinin, 2013; Winograd and Flores, 2004).

There has been growing interest in the application of Leontiev's activity theory to Human-Computer Interaction (HCI), with tool-mediated and goal-oriented human activity as the basic unit of analysis in the design of interactive artefacts (Nardi, 1996). Computational systems, tools and symbols are – increasingly – among the artefacts that collectively constitute human activity. Computational representations gain meaning from their combination in use with each other and with symbols in other more traditional media such as speech, gesture and writing (Chalmers, 2005). Borba and Villareal suggest that knowledge is produced by a collective of humans-with-technologies and not by humans alone (Borba and Villareal, 2005).

In educational contexts, the advent and popularisation of interactive, multimedia technology have profoundly changed the standard ways of performing traditional activities like writing, communication and planning. It is a new, qualitatively different extension of memory, which introduces other ways of thinking than linear reasoning, based on simulation, experimentation, and a 'new language' involving writing, orality, images and instantaneous communication (Borba and Villareal, 2005). Computers can provide 'coaching', with new possibilities for interpretation and action (Winograd and Flores, 2004). Digital technologies provide new ways of explicitly and dynamically linking multiple representations, helping the learner to map between them in ways that are not available with traditional media (Scaife and Rogers, 2005). The wider range of representational tools created by new technologies has motivated research into new possibilities for addressing the difficulties of learners in establishing mappings between concepts and external representations. It has been suggested by many that digital representations can reinforce the link between abstract and concrete, thus helping to externalise ideas and processes (Clements, 1999; Suh and Moyer-Packenham, 2007).

More specifically, key advantages of digital representations for learning include: combination of multiple forms of representations (audio, video, text, animations, graphics); interactivity (allowing the user to manipulate these representations); provision of feedback; and ability to keep trace of and undo past actions (Clements, 1999; Kaput, 1992; Moyer, Bolyard and Spikell, 2002; Scaife and Rogers, 2005). More broadly, the digital also has the potential of creating representational changes not easily replicated in the physical world (Manches and Price, 2011).

If computer simulations are said to help to bridge the gap between representations, tangible technologies, which can be seen as digitally augmented physical manipulatives, go one step further to provide the possibility of establishing explicit connections between the actual physical artefact and the corresponding abstract representation.

The case of learners with intellectual disabilities

Since the 1990's, there has been a renewed interest in constructivist, hands-on approaches, with a sense-making orientation to learning rather than task completion, for special education (Bell, 2002; Cawley and Parmar, 2001; McCarthy, 2005; Scruggs and Mastropieri, 1994). Students with mild disabilities have been found to engage actively in the construction of scientific knowledge through the exploration of materials, and consequently remember and comprehend more than when directly provided information (Scruggs and Mastropieri, 1994). Students with intellectual disabilities commonly have language and reading deficits that hinder their ability to generate and construct meaning from text (Cawley and Parmar, 2001; McCarthy, 2005), and thus their performance in traditional textbook approaches is extremely deficient. The alternative hands-on approach is more likely to succeed for these children because of the reduced emphasis on the use of text and abstract textual learning in favour of more concrete experiences and physical interaction with the phenomena in study (learn by doing) (Mastropieri, Scruggs and Magnusen, 1999; Scruggs and Mastropieri, 1995; Scruggs et al., 1993).

The use of manipulatives is especially encouraged for students with intellectual disabilities (Homan, 1970; Marsh and Cooke, 1996; Marzola, 1987). In the beginning of the twentieth century, Montessori, finding that she had no medical treatment available for intellectually disabled students, obtained good results through systematic use and manipulation of the physical educational materials she created (Kirk and Gallagher, 1979). Throughout the years, research in learning disabilities has shown the importance of the concrete phase of instruction (Underhill, Uprichard and Heddens, 1980) and higher levels of achievement in mathematics problem-solving and understanding when using manipulatives (Larson and Slaughter, 1984; Marsh and Cooke, 1996). Being motivational, manipulatives can benefit memory and understanding (Halford and Boulton-Lewis, 1992; McNeil and Jarvin, 2007) and increase on-task behaviour and attention span (Marzola, 1987; Mix, 2010), which are typical difficulties of children with intellectual disabilities, as described in Chapter 2. Butler et al. (2003) showed that the concrete-representational-abstract instructional method was more effective in understanding fraction concepts to students with maths disabilities, than the representational-abstract instructional approach.

There has also been an increased emphasis on the role of the teacher in helping children construct meanings based on their existing ideas and experiences, and on the process of scaffolding for creating opportunities for children with intellectual disabilities to engage with new ideas (Bell, 2002) and actively reason, thus learning more via active exploration with concrete materials that facilitate knowledge construction and problem-solving (Cawley and Parmar, 2001; Mastropieri, Scruggs and Magnusen, 1999; Scruggs et al., 1993).

Through first-hand experience of objects, situations and phenomena (Cawley and Parmar, 2001; McCarthy, 2005) children with learning disabilities are expected to: develop an awareness of, and interest in themselves and their immediate surroundings and environment; join in practical activities that link to ideas; use their senses to explore and investigate; and develop an understanding of cause and effect by observing, measuring, classifying, comparing, predicting, and inferring (McCarthy, 2005; QCA, 2001). Hands-on curricula may improve the experiential background for students who have had limited experiences in their daily life, and relate students' cultural backgrounds and real-life situations to formal learning (Salend, 1998; Scruggs et al., 1993).

A number of studies provide evidence of the benefits of hands-on approach to science for students with intellectual disabilities. Shymansky, Kyle and Alport (1982), Bay et al. (1992), DeLuca (1997), and Mastropieri et al. (1998) all found that students taught through hands-on approaches to science outperformed those in the textbook-based classes. When comparing textbook-based and inquiry-based approaches in science learning in special education classrooms, Scruggs et al. (1993) found that "when students were taught by experimental, more indirect methods, they learned more, remembered more, and enjoyed learning more than when they were taught by more direct instructional methods" (p. 11). In several studies reported by Mastropieri, Scruggs and Magnusen (1999), which used a variety of experimental designs and methodologies, students scored higher in post-tests when they were taught through inquiry-based methods and materials, and showed great preference for such approach (Magnusen and Mastropieri, 1998; Scruggs and Mastropieri, 1994). Students also found they tried harder and learned more through hands-on methods. Scruggs and Mastropieri (1994) suggest that students presented to the inquiry-based approach acquired a deeper understanding of scientific concepts, in contrast with the more superficial comprehension that often results from traditional textbook-based methodologies. Mastropieri, Scruggs and Magnusen (1999) found that activity-oriented science increased manipulative skills, science process skills, and self-perception, leading to more appropriate and on-task behaviour and attention; as well as for generalisation of learning across a broad range of disabilities. Bay et al. (1992) also found that discovery learning was more effective to assist students with learning disabilities in their ability to generalise. Mastropieri et al. (1998) noted that the effective implementation of hands-on instruction leads to successful participation of students with a variety of disabilities and successful achievement. It is suggested that activity-centred science programs also generate positive attitudes towards learning, as students tend to perform better at tasks when they enjoy what they are doing (McCarthy, 2005).

In addition, such approach also creates opportunities for everyone to participate, encouraging collaboration and cooperation with peers and making it easier to include students with intellectual disabilities in regular classrooms

(Atwood and Oldham, 1985; Mastropieri, Scruggs and Magnusen, 1999). The open style of interaction invites students to express their opinions safely (Scruggs and Mastropieri, 1994). Scruggs and Mastropieri (1994) and Mastropieri et al. (1998) found that peers, particularly students with learning disabilities, lent each other effective assistance in hands-on science activities and general assistance as needed. In general, social interactions seemed to facilitate learning by creating a positive atmosphere.

Having said that, some drawbacks of hands-on approaches are also reported. Students with intellectual disabilities may have problems with experimentation consisting of poorly structured activities (Scruggs et al., 1993), as they usually need specific, well-defined tasks. It should not be assumed that these students are able to compensate for their learning disabilities for themselves in a multimodal environment (Carlisle and Chang, 1996). Fear of failure can also be a barrier for students to dare to explore an open environment without specific rules and guidance. Teachers must coach students through the reasoning process, directing their thinking, and not leave them to a variety of materials and ways to discover concepts on their own (Carlisle and Chang, 1996; Mastropieri, Scruggs and Magnusen, 1999; Scruggs and Mastropieri, 1994). Science lessons in special classes observed by Scruggs and Mastropieri (1994) were highly structured, with a clear and redundant presentation of objectives and information, and guided interaction. Open-ended questioning often results in whether cue-seeking or imitative answers ('outerdirectedness'), or no response, whereas specific questions may lead to meaningful replies (Scruggs and Mastropieri, 1994).

It is important to note that even when they are able to construct knowledge from hands-on activities, this is still not an easy process for students with intellectual disabilities, and requires a lot of teacher's effort and attention, which may not be possible in inclusive mainstream settings (Scruggs and Mastropieri, 1994). Also, such practical activities may lead to more opportunities for inappropriate behaviour (Scruggs et al., 1993). Having physical materials available for students may create a potentially hazardous environment and strict behavioural rules become necessary. Students can become inattentive and off-task when materials do not provide sufficient stimulation (Scruggs and Mastropieri, 1994). Therefore, inquiry-based activities require more teacher preparation and organisational and behaviour management skills (Mastropieri, Scruggs and Magnusen, 1999).

Implications

The present research is rooted in embodied cognition and constructivist principles, adopting the belief that students benefit more from active, practical experience with materials than from passive, listening of information and facts, and agreeing with Dewey's views that knowledge grows through analysis and rearrangement of facts, which is not a purely mental process, but has its basis in practice (Dewey, 2001). The present work does not focus on Piagetian movement from concrete to abstract as a sign of cognitive development, but agrees with Piaget's belief on the importance on physical actions as part of the learning process, combined with the process of discovery through exploration of external representations.

This focus on physical experimentation is especially recommended for students with intellectual disabilities, for providing them with concrete experiences. Also, according to Vygotsky, intellectual disabilities can be addressed through the provision of auxiliary cultural tools, as the child is unable to effectively use their own 'natural resources' (Vygotsky and Luria, 1993). The research looks at how students with intellectual disabilities may be able to derive abstract concepts from the concrete instances presented by external representations (tangible technologies) that mediate the learning process, providing an environment that encourages exploration through physical action. Furthermore, tangible technologies also allow setting up hybrid physical-digital simulations, which is a potential form of (i) mirroring empirical processes more realistically and situating formal learning within authentic contexts; (ii) addressing the problematic process of linking physical artefacts with their symbolic representations and concepts. In the empirical studies, students went through a process of guided discovery learning, where a substantial amount of feedback and scaffolding was provided by the tangible technologies themselves. This might facilitate the work of the teacher in inclusive settings, where the demand for teacher's attention during discovery learning activities with students with intellectual disabilities may not be realistic. The intention is to ensure that opportunities for actual learning are created, addressing the lack of structure and consequent concerns over the effectiveness of unassisted discovery learning, which becomes even more problematic in the case of students with intellectual disabilities. This research adds to the fruitful debate, in which Alfieri et al. (2011), Chi (2009) and Mayer (2004) are engaged, on providing guidance through productive forms of scaffolding and feedback to enhance discovery learning processes.

Introducing tangible technologies in educational settings can contribute to Dewey's appeal for "more actual material, more stuff, more appliances, and more opportunities for doing things" (2001, p. 162), to bridge the gap between the passive learning method that still dominates, and the modern theories that put bodily experience at the basis of learning.

Chapter 4 – Tangible technologies

Since computers were created, Human-Computer Interaction (HCI) evolved from configuring circuits, to the use of low-level programming languages followed by command-line interfaces, to finally reach the revolutionary 'graphical era' (Dourish, 2001), when a two-dimensional space was provided to directly manipulate visual elements, with a move from linguistic to spatial orientation. Tangible and embodied interaction represent a next step in the HCI paradigm, bringing computation and information more fully into the physical world, reconsidering the nature and uses of computation, capitalising on people's physical skills and familiarity with objects from the physical world, and thus providing an interaction paradigm closer to what is considered 'natural' (Dourish, 2001; Ullmer and Ishii, 2001). This chapter presents the origins of the tangible paradigm and the adopted definition of tangible technologies. Then, the application of tangibles in the educational field is discussed in terms of benefits and theoretical frameworks, and incipient research in the area of tangibles and learning difficulties is presented, contextualised within the broader area of technologies for special needs.

Defining tangible technologies

The origins of the HCI paradigm that gave birth to tangible technologies can be traced back to the early 1990's, when Mark Weiser and collaborators at Xerox PARC developed the pioneer vision of ubiquitous computing ('ubicomp'). Stimulated by the work of his colleague anthropologists, Weiser realised computers' complexity, high demand for attention, and tendency to isolate people. The research program on ubicomp intended to reposition computers in the environmental background and redefine the relationship between humans and technology in a post-PC era, where computation would move to the environment where human activity unfolds (Weiser, Gold and Brown, 1999). Such paradigm is rooted in the theoretical frameworks of situated cognition, phenomenology and embodied cognition (Chapter 3), moving away from the positivist cognitive perspective that poses a strong separation between the mind and the external world. In spite of the fact that cognitivism has been at the basis of a large body of research in traditional HCI and has its merit and place in the design of many computing systems, such theoretical perspectives are no longer considered sufficient for holistically understanding human cognition (Antle, Corness and Droumeva, 2008). Alternatively, the embodied interaction approach is predominantly based on the idea that human thinking and experience of the world is tied to action, and cannot be separated from the body (Dourish, 2001; Shaer and Hornecker, 2010). Therefore, according to this new HCI paradigm, computation should be seamlessly integrated into objects and activities of everyday life, to retain the richness and situatedness of physical interaction and provide fluid transitions between the digital and the physical in human practices (Shaer and Hornecker, 2010).

A number of landmarks accompanied the conception of ubicomp. In 1995, Fitzmaurice et al. introduced the concept of Graspable User Interfaces (Fitzmaurice, Ishii and Buxton, 1995), building on intuitive knowledge people have of everyday objects and taking advantage of their physical affordances by using wooden blocks as handles to manipulate digital objects. The aim of the authors was to increase direct manipulation of graphical user interfaces. Graspable interfaces were a precursor of Tangible User Interfaces (TUIs), introduced two years later in the HCI community through Ishii and Ullmer's definition of 'tangible bits' (1997). The core concept was that digital bits could be 'grasped and manipulated' if coupled with everyday physical objects and architectural surfaces, bridging the gap between the 'cyberspace' and the physical environment. According to Antle, "tangible systems can help the user to understand the real world *in* the real world" (2007, p. 1, emphasis added). While directly manipulating digital representations instead of typing computer commands moved interfaces closer to 'real-world' interaction, new interaction styles like tangible increase the 'realism' of artefacts allowing users to interact even more *directly* with them, through actions that correspond to daily practices within the non-digital world (also called Reality-Based Interaction) (Jacob et al., 2008).

Although the definition of tangible interfaces is still open to interpretation, the research community has come to a general consensus according to which an artefact is tangible when it embeds digital data (e.g. graphics and audio) in material forms (i.e. physical objects), yielding interactive systems that are computationally mediated, but generally not identifiable as 'computers' in the traditional sense (Hornecker and Buur, 2006; Ullmer and Ishii, 2001). In very general lines, tangibles consist of hybrid physical-digital representations that usually share the following basic paradigm: (i) the user manipulates physical object(s) via physical gestures; (ii) a computer system detects this and (iii) gives feedback accordingly (Fishkin, 2004).

In tangible systems, the distinction between 'input' and 'output' is less obvious and sometimes inexistent (Fishkin, 2004; Shaer and Hornecker, 2010; Ullmer and Ishii, 2001). Users act within and touch the interface itself, bodily interacting (within the physical space) with physical objects that are coupled with computational resources, and that can provide immediate and dynamic haptic, visual or auditory feedback to inform users of the computational interpretation of their actions (Shaer and Hornecker, 2010). In general, there is no single point of interaction – an action can be distributed across multiple devices or achieved through coordinated use of these devices (Dourish, 2001).

As an illustrative example, in the 'Urp' tangible interface for urban planning (Figure 4.1), users manipulate architectural physical models on a surface that depicts a city map. The users can move the models of buildings on the surface to find their optimal location in regard to different climate conditions, setting the amount and direction of sunlight and wind, and immediately seeing the corresponding effects projected on the surface as graphical representations (i.e. shadows and wind flow, respectively). This allows them to easily explore and visualise a number of possibilities when planning urban design.

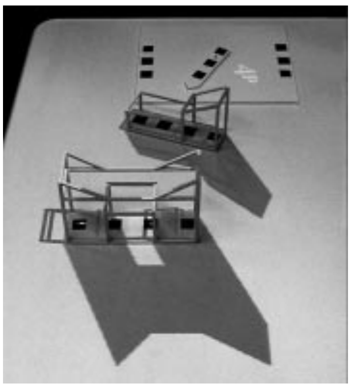


Figure 4.1: Representations of buildings in Urp
Source: (Underkoffler and Ishii, 1999)

The meaning of physical representations

One basic idea behind the tangible paradigm is that people typically interact with physical things that convey information not only through their encoded symbolic meaning, but also through their physical properties (Dourish, 2001). A key aspect of the concept of tangible technologies is that the physical components of a tangible system are objects of interest, playing a central role as physical representations and/or controls for digital information (Ullmer and Ishii, 2001). Such physical representations have associated meanings relevant to the context of the system, conveyed through affordances that guide the user interaction (Dourish, 2001; Gaver, 1991). For example, in the Urp system aforementioned, physical models of buildings are used as physical representations of actual buildings (Underkoffler and Ishii, 1999). Their physical forms, position and orientation within the system have central roles in the interaction (Ullmer and Ishii, 2001). Although traditional user interface devices such as keyboards and mice are also physical artefacts, their physical form and position hold little representational significance – the mouse is a generic mediator to control the graphical interface's cursor, only providing simple information about movement in two dimensions (Dourish, 2001; Ullmer and Ishii, 2001).

An alternative, action-centric view focuses on what can be done with the resources, rather than on the resources themselves and the information they are meant to represent. This perspective argues for tangibles as *resources for action* while criticising the focus on representations for being 'data-centric' and thus lacking contextualised interaction analysis (Fernaeus, Tholander and Jonsson, 2008). Although a focus on resources for action allows creating complex and powerful systems, mappings between representations and meanings become less clear, which can be problematic in educational contexts, particularly in the case of children with intellectual disabilities. Even in the case of physical representations that have a clear associated meaning and/or hold a conceptual metaphor in relation to the physical world, a number of design possibilities for symbolic mediation of human activity can be created, as discussed in Chapter 3. Such mappings between representation and meaning are not necessarily straightforward, and children with intellectual disabilities may not grasp the relationships imagined by the designer. The tangible systems used in the present research have different levels and types of representational mappings (Chapter 7). The consequences of each type of design are analysed in terms of support provided for mediating these children's exploratory activity.

The role of physical engagement

In desktop computing, physical performance of work has homogenised. With keyboard and mouse interfaces, the use of our bodies for writing a paper is the same as for editing photographs, playing music and communicating with friends. However, when a child plays with physical building blocks, they engage with them in very different ways from a screen-based equivalent virtual representation of the blocks. So, the interaction style of desktop systems constrains gestural abilities and thus is likely to hinder the user's thinking and communication, according to studies that have demonstrated the importance of gesturing for cognition (Cook, 2007; Edwards, 2009; Goldin-Meadow, 2000). Furthermore, as user actions are the same across applications, kinaesthetic memory (i.e. ability to sense, store and recall own muscular effort, body position and movement to build skill) can only be leveraged to a limited extent (Klemmer, Hartmann and Takayama, 2006).

With tangible computing, the computer is getting 'out of the way' in favour of a more direct, physical experience of interaction (Dourish, 2001). Physical embodiment of computation induces a dialogue through gesture and physical touch (Baskinger and Gross, 2010). As tangible interaction means moving objects around and interacting through or with a variety of physical artefacts instead of traditional graphical interfaces input devices like mice, there is a negotiable relationship between body configuration and computational artefacts, in terms of distance between user and artefact, orientation of user to objects and type of technology used (like sensors, tracking and displays) (Dourish, 2001; Hornecker and Buur, 2006). This type of interaction, including the employment of bi-manual and haptic interaction skills, is believed to improve accessibility and usability (Zaman et al., 2012). By taking advantage of multiple senses and the multimodality of human interactions with the physical world, tangibles provide a rich and supposedly pleasurable multi-sensory experience of digital information, making computation fit more naturally with the everyday world, and at the same time enriching human experiences with the physical (Dourish, 2001; Hornecker and Buur, 2006; Ishii and Ullmer, 1997).

The definition of tangible interfaces presented in this chapter shows that, as previously suggested in the present work, tangibles can serve as external representations that mediate people's cognitive activities, and with which people can engage physically, constructing meaning through the use of their bodies and senses. The tangible paradigm is thus very much in line with the theoretical framework of this thesis, drawing on the theories of external and embodied cognition. Narrowing down to the educational domain, the next section shows that tangibles are also aligned with principles of constructivism, and explains why tangible technologies are increasingly popular for learning.

Tangibles for learning

Education is one of the main areas of application of tangibles, as their specific properties and capabilities represent promising novel opportunities for learning (O'Malley and Fraser, 2004; Shaer and Hornecker, 2010). The focus of the tangible field on education is not surprising, given that many of the advantages of moving digital interfaces into the physical world seem especially beneficial for schoolchildren (Horn et al., 2009). Since computers were introduced in schools, there has been a gap between the abstract, virtual world of traditional digital media and the physical, material world of educational artefacts (Eisenberg et al., 2003; Ishii and Ullmer, 1997). A large number of 'virtual manipulatives' were created that are graphical on-screen counterparts of physical materials (McNeil and Jarvin, 2007), and although their benefits have been well described (Clements, 1999), they lack the proved value of the haptic interaction provided by the physical manipulatives, as discussed in Chapter 3. Despite the value and place of desktop-based applications, tangible technologies can provide richer sensory experiences through the interweaving of computation and physical materials, extending the intellectual and emotional potential of children's artefacts and integrating compelling and expressive aspects of traditional educational technologies with creative and valuable educational properties of physical objects. Thus, when building tangible artefacts, educational designers go beyond screen-based applications and create systems that are more diffused in the physical environment (Eisenberg et al., 2003). By providing hands-on experimentation with embedded computer technologies, tangibles build on the alleged benefits of educational manipulatives and constructivist learning (Parkes, Raffle and Ishii, 2008).

Potential benefits for learning

The advantages brought by tangible technologies to the learning process that are commonly reported in the literature are derived from theoretical educational arguments as well as from incipient empirical research. Such advantages are centred on characteristics that are part of the definition of tangibles (physical interaction and physical-digital mappings) and on aspects that are said to be a natural consequence of such characteristics (exploration, collaboration, accessibility). This section compiles the main alleged benefits of tangibles for learning according to such categories.

Physical interaction and manipulation

Research on tangibles for learning draws on the importance given by Piagetian developmental theory to manipulation of physical objects for supporting and developing thinking (Marshall, 2007). As sensory engagement is part of children's natural learning process, tangibles are believed to contribute to the constructive process of building knowledge through physical experience (Zuckerman, Arida and Resnick, 2005). When interacting with tangible systems, children can engage in a range of physical actions and spatial abilities (Antle, 2007; Price, Sheridan and Pontual Falcão, 2010), which allegedly supports the development of a mental model of the task (Antle, Droumeva and Ha, 2009). In particular, tangibles give support to epistemic actions, i.e. non-pragmatic manipulation of artefacts to better understand a task's context, facilitating mental work (Shaer and Hornecker, 2010). As children develop many ideas about the world from their informal experiences through physical actions, a potentially effective way to help children draw upon important concepts from these experiences is to use artefacts to foster similar physical actions (Manches and Price, 2011).

Physical-digital mappings

Tangibles provide mappings between digital representations and physical objects that reinforce links between the concrete and the symbolic, usually less clear in non-augmented physical artefacts (Clements, 1999). An example is dynamically mapping the movement of a physical ball to abstract concepts of speed and acceleration, as with BitBall (Figure 4.11). In order to provide support for learners to use external representations, computational objects should not only offer affordances for action, but also represent information in their resulting spatial configurations (Antle, 2009; Price, Sheridan and Pontual Falcão, 2010). For example, in the Urp system (Figure 4.1) shadows of buildings are shown according to the intensity and direction of sunlight adjusted by the user. The shadows are shown as digital representations projected next to the physical model of the buildings, providing a clear physical-digital mapping, and dynamic digital representations that respond to the user's actions.

Exploration and discovery learning

According to Scaife and Rogers (2005), children's creativity and scientific investigation can be well supported by manipulating digitally augmented objects in the 3D space as representational devices, especially when this physical activity leads to multimedia effects in the digital space. Tangible technologies adopt natural metaphors of object usage and take advantage of skills, experience and assumptions about the physical world (Antle, 2009; Parkes, Raffle and Ishii, 2008), allowing children to combine and recombine the known and familiar in new and unfamiliar ways. This enables novel and unexpected combinations of activities or events, encouraging creativity and reflection through discovery and participation in a productive process of collective exploration and knowledge construction (Pontual Falcão and Price).

Collaboration

The opportunity to work collaboratively is an added benefit of dealing with physical objects (Rogers et al., 2008; Scarlatos, Landy and Qureshi, 2002). Tangibles have both the space and the affordances (physicality of inputs and spatial distribution of the setup) for multiple users (Antle, 2007; Stanton, Neale and Bayon, 2002). They can be shared, passed around and independently manipulated in a meaningful way by multiple users (Horn et al., 2009; Ullmer and Ishii, 2001), supporting face-to-face social interaction (Hornecker and Buur, 2006). Tangibles are thus claimed to improve support for co-located collaborative interaction, providing better perceptual access (Brave, Ishii and Dahley, 1998; Horn et al., 2009; Hornecker and Buur, 2006; Zuckerman, Arida and Resnick, 2005). Awareness of others' actions and visibility is usually greater in tangible systems than when users are sharing a vertical graphical interface (Horn et al., 2009; Stanton, Neale and Bayon, 2002). Sharing the physical and virtual resources of the system contributes to balanced levels of participation, particularly through action.

Accessibility

Tangibles are said to allow control of one's own learning process, thus supporting learners at multiple levels (O'Malley and Fraser, 2004; Raffle, Parkes and Ishii, 2004). According to Resnick (2006), tangible systems can provide conceptual leverage that enables children to learn concepts and develop schemata which might otherwise be difficult to acquire. Computationally enhanced construction kits, for example, are said to make concepts accessible on a practical level that are normally considered to be beyond the learner's abilities and age-related level of abstract thinking (Shaer and Hornecker, 2010). Analogies between a simulated abstract behaviour and real life examples meaningful to children facilitate comprehension, especially for children with learning disabilities (Zuckerman, Arida and Resnick, 2005). In addition, tangibles' physical affordances provide ways of implicitly designing physical constraints to limit – and thus simplify – the solution space. Physical constraints can decrease the need for learning explicit rules and lower the threshold for using the artefact (Shaer and Hornecker, 2010). Such characteristics, along with the multimodal interaction and the familiarity of the physical devices, make tangibles particularly intuitive and accessible for novices, younger children and people with learning disabilities (Schneider et al., 2011; Zuckerman, Arida and Resnick, 2005), including the possibility of participating through action without verbal communication (Rogers et al., 2008; Stanton et al., 2002).

The potential benefits of using tangibles in educational contexts are well aligned with the theoretical foundations and the goals of the present research. Firstly, tangibles allow physical engagement as a way of interacting with concrete materials to explore concepts, as advocated by theories of embodied cognition, constructivism and discovery learning. Secondly, tangibles help to bridge gaps in mappings between concrete and symbolic representations, known to be problematic when using symbolic mediators in educational activities. Thirdly, tangible interfaces lend themselves to collaborative, exploratory activities, creating a suitable environment for discovery learning, which is a recommended but yet problematic approach for children with intellectual disabilities, and thus under investigation in this research. Lastly, tangibles are believed to be a more accessible type of technology, being therefore recommended for children with various kinds of needs. However, tangible technologies represent a novel paradigm of human-artefact interaction that is only starting to be investigated (Shaer and Hornecker, 2010). Eventual learning gains are reported in rather hesitant and informal accounts of empirical studies, as most findings consist of anecdotal descriptions of children's enjoyment and engagement in discovery collaborative activities with the new technologies. In particular, studies that analyse intellectually disabled children's interaction with tangibles are virtually inexistent. Although there seems to be a lot of potential in using tangibles with this population, the field is in need of extensive further research.

Theoretical frameworks

A few key initiatives attempt to go beyond reporting empirical findings, providing theoretical frames to tackle different aspects of child-tangible interaction. Zuckerman et al. have focused on the strong relationship between tangibles and traditional manipulatives to propose a framework according to Montessori's and Froebel's principles (Zuckerman, Arida and Resnick, 2005). The authors define Froebel-inspired Manipulatives (FiMs) as building pieces that enable children to design 'real-world' objects and physical structures (e.g. a castle made of building blocks); and Montessori-inspired Manipulatives (MiMs) as sets of building blocks primarily focused on modelling conceptual abstract structures (e.g. Cuisinaire rods to represent numerical proportions). The classification is extended to digital manipulatives, defined as computationally-enhanced versions of physical objects aimed at expanding the range of concepts that children can explore through direct manipulation (Resnick et al., 1998). Two types of digital MiMs were developed (Zuckerman, Arida and Resnick, 2005), but it is not clear how this rather restricted classification can actually help and guide the development of tangibles for learning.

Taking a broader perspective, Rogers et al. proposed a conceptual framework for children interaction in mixed reality environments, aiming at investigating levels of exploration and reflection through new forms of physical-digital embodiment (Rogers et al., 2002). The authors proposed four possible 'transforms' between virtual and physical actions and effects, categorised in terms of their level of familiarity for children - the most familiar being physical action causing a physical effect, and the least familiar being digital action causing a physical effect. Children experienced the transforms through activities with Chromarium (Figure 4.2), an environment for experimenting with colour mixing through physical coloured blocks and associated digital representations. Analysis indicated that physical interaction and unfamiliar transforms led to more communication, reflection and exploration.

Figure 4.2: Chromarium
Source: (Gabrielli et al., 2001)

Marshall et al. base their analysis of tangibles for learning on the concepts of 'expressivity' and 'exploration' (Marshall, Price and Rogers, 2003). Expressive artefacts are said to embody the learner's actions and allow them to focus on the external representation of their activity. Aligned with Papert's constructionism (Papert and Harel, 1991) and the theory of external cognition, such approach is believed to support objective reflective thought. An example of an expressive tangible is Topobo (Figure 4.3), a constructive assembly system with joint pieces that have kinetic memory.

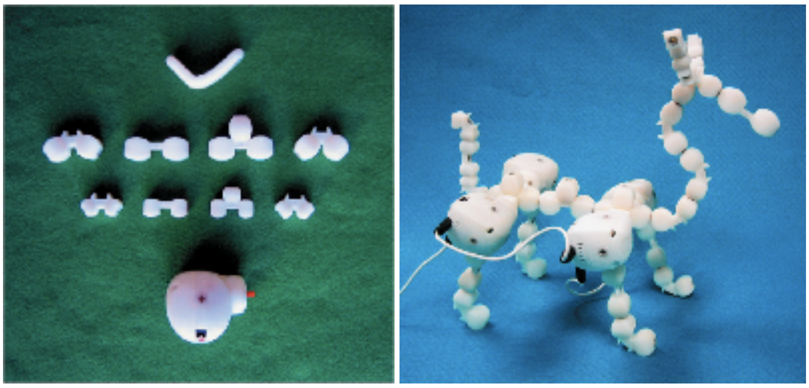


Figure 4.3: Topobo pieces (left) and creature (right)
Source: (Raffle, Parkes and Ishii, 2004)

With Topobo, children can create and then animate animal forms by pushing, pulling, and twisting them, and observe the system play back those motions (Raffle, Parkes and Ishii, 2004).

Exploratory artefacts do not embody the learner's activity, but make the learner investigate a model made by others. For instance, Illuminating Light (Figure 4.7) (Underkoffler and Ishii, 1998) is an exploratory tool where simulated light beams are projected on a surface onto plastic objects that represent prisms, lenses and mirrors. The system displays optical phenomena, showing angles, distances, and path length, as the user manipulates the physical objects. Such activity of experimenting and observing allows the exploration of the theoretical model represented by the system, possibly leading to an understanding of the laws that govern the behaviour of light beams.

Despite their classification of expressive and exploratory *artefacts*, Marshall et al. suggest that a same tool may serve both expressive and exploratory *activities*, depending on how it is used (Marshall, Price and Rogers, 2003). Also, the authors argue that during activities a switch between artefact presence-at-hand and readiness-to-hand is productive for learning, allowing standing back from the experience and reflecting objectively upon it (Ackermann, 1996). Marshall et al. recommend their framework as a way of conceptualising tangibles in terms of learning and interaction styles. Later, Marshall included the classification of exploratory and expressive activities as one of six perspectives proposed within a broader analytical framework to guide research and development of tangible interfaces for learning (Marshall, 2007). The framework, depicted in Figure 4.4, presents empirical findings, theoretical frames and future directions regarding this and five other aspects: possible learning benefits; typical learning domains; integration of physical and digital representations; concreteness and sensory directedness; and effects of physicality. Marshall highlights the infancy of the field of tangibles for learning and the need for further research that provides a better comprehension of which elements of tangible interfaces are critical in supporting learning activities.

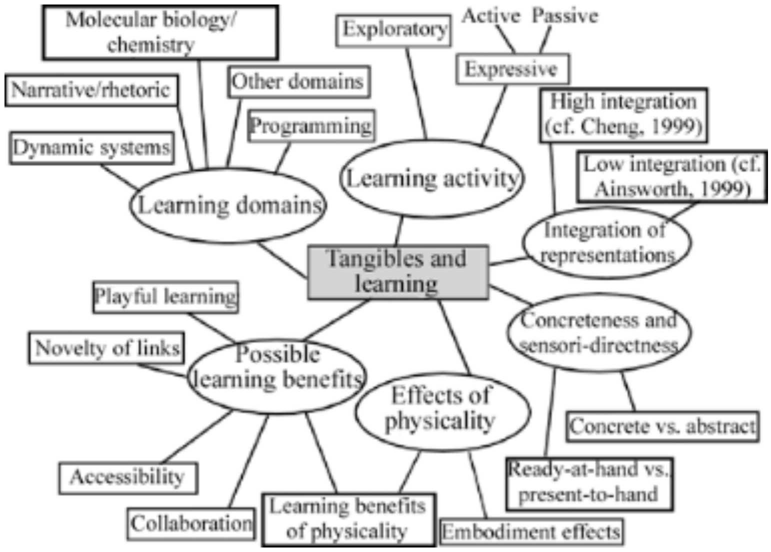


Figure 4.4: Marshall's framework on tangibles and learning
Source: (Marshall, 2007)

Taking a more design-oriented perspective, Antle proposes the Child Tangible Interaction (CTI) framework (Antle, 2007) to look into the ways in which augmentation can support children's cognitive processes, and the reasons why. The framework is grounded in developmental theories about how children develop intelligence as active learners embedded in their physical, social and spatial interactions with the world. Antle's work has as a premise the importance of embodied cognition for designing systems for children. The CTI framework relates five themes to features of tangible systems, as follows:

- *Space for action*: Antle draws on embodied cognition and constructivist theories to advocate the importance of bodily engagement with physical objects to facilitate active learning, and body-based human-system interaction. The importance of epistemic actions as external scaffolding is highlighted as a strategy to offload cognitive processes by manipulating the environment. Tangibles are inherently spatial and afford opportunities to capitalise on children's developing repertoire of physical actions and spatial abilities.

- *Perceptual mappings*: tangibles' physical-digital mappings must be designed in terms of relationships between how things appear to children and how things respond. Therefore, age-appropriate perceptual affordances must be designed to provide opportunities for action.
- *Behavioural mappings:* Antle suggests that behavioural mappings between input behaviours and output effects should promote cognitive mode switching between experiential and reflective cognition, with the artefact switching between Heidegger's concepts of presence-at-hand and readiness-to-hand. Antle draws on Piaget's theory to point to the importance of children moving from the active experiential mode to the reflective mode, in order to acquire new understandings. A successful design of behaviour mappings must take into account cause and effect relationships as understood by children, especially in terms of temporal precedence, co-variation, and temporal and spatial contiguity.
- *Semantic mappings:* understanding multiple representations and referents is challenging for young children. Semantic mappings between different representations (physical and digital) must consider children's understandings of what things mean in various representational forms. This includes the reciprocal nature of physical and mental representations, and the grounding of abstract concepts in body-based and concrete spatial schemata.
- *Space for friends:* tangibles have space and affordances for multiple users, and thus should facilitate children's collaboration. Antle suggests that the system should support but not require collaboration, provide multiple input devices and a protocol for transfer of control, and give support to imitation through intentional affordances.

Price et al. acknowledge Marshall's six perspectives for analysis and Antle's five themes for design, but suggest that a more detailed framework for structuring research within such aspects is needed (Price et al., 2008). Price's framework focuses on the relationships between external representations, action and artefact, as a way of conceptualising physical-digital links and analysing their role for shaping cognition in more fine-grained categories. The framework, depicted in Figure 4.5, is composed of four parameters:

- *Location* refers to the distance in space between physical and digital components of the system, which has an impact for cognition in terms of making links between object, action and representation. Location can be 'discrete' (separate physical input and digital output), 'co-located' (contiguous input and output) or 'embedded' (coincident input and output).
- *Dynamics* relates to the flow of information throughout the interaction and includes the categories of 'causality' and 'intentionality'. Causality refers to system's feedback to user actions, being 'simple' when this feedback is immediately subsequent and conveys a direct association between action/object and effect; and 'complex' when feedback depends on time and/or multiple actions. Intentionality is classified as 'intentional' when actions lead to expected effects, and 'serendipitous' when digital effects are inadvertently triggered according to pre-determined configurations.
- *Correspondence* depicts the metaphors involved in the nature of representations of artefacts and actions upon them. Correspondence encompasses the categories of 'physical', 'representational' and 'action'. Physical correspondence refers to the mapping between the physical properties of the objects and the learning concepts. It can be 'symbolic' when the object has little or no characteristics of the entity it represents; or 'literal' when the object's physical properties are closely mapped to the metaphor of the domain it is representing. Representational correspondence refers to mappings between representations and the learning domain. Such mappings can vary in levels of associations from 'direct' to 'ambiguous', between symbol and symbolised, according to the

concept being displayed. Action correspondence can refer to 'manipulation', which is the type of action performed with the objects; and 'movement', which refers to the characteristics of the action, like duration, flow, regularity and directionality.

- *Modality* encompasses visual, tactile and audio types of representations, and is important for understanding the effects, for the learner, of different dynamic representation modalities when integrated with each other and with physical interaction.

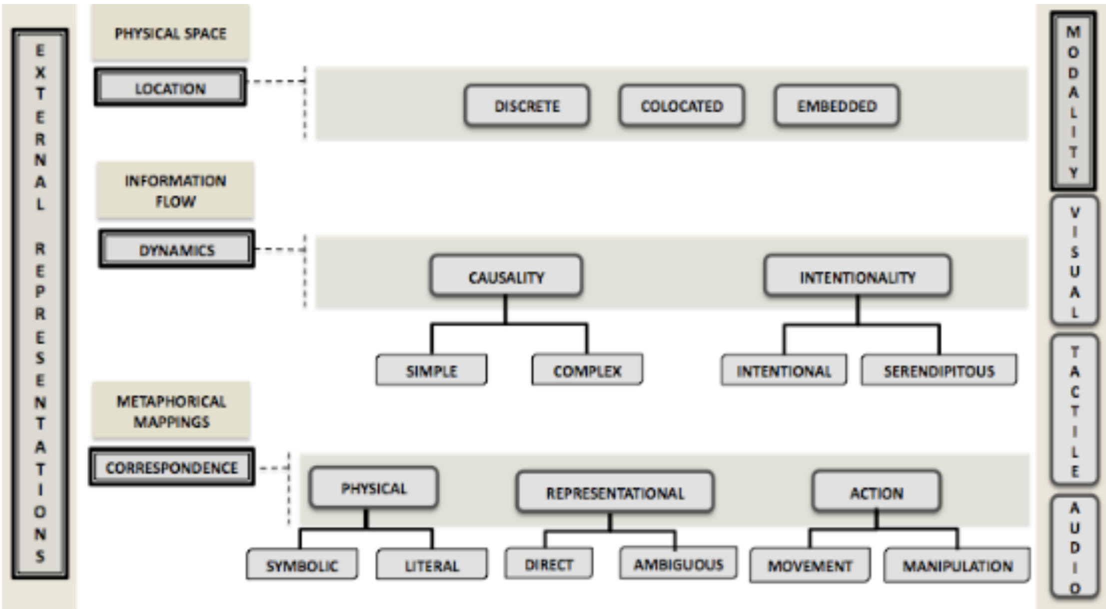


Figure 4.5: The representation framework
Source: (Price et al., 2008)

The frameworks presented in this section vary in granularity, orientation and scope. Zuckerman et al. provide a rather scope-limited classification of digital manipulatives that takes as differentiating aspect the concreteness versus abstractness of representations. Marshall, Price and Rogers provide a high-level theoretical discussion looking at the nature of the interactions in terms of expressivity and exploration, but do not go into details on the characteristics of tangibles in relation to the two categories. Marshall's following proposal of framework aims at structuring the research space, and thus is much broader in scope, but remains at a high-level, rather philosophical discussion. Finally, both works of Antle and Price attempt to be more specific on mapping the characteristics of tangibles to possible effects for learning. Antle explicitly assumes a more design-oriented perspective, aiming at helping developers to produce systems that are adequate to children's interaction, and whose characteristics will facilitate learning. Price stands from a more theoretical point of view to describe a number of very specific categories that try to cover all aspects of tangible interaction and relate them to representations for learning. Although distinct in form and vocabulary, the core concepts of these two frameworks are much related, particularly in respect to mappings between different types of representations, and couplings between the children's actions and the corresponding effects.

The frameworks on tangibles and learning presented in this section help structuring the research space and pointing to key aspects to be taken into account when designing or using tangibles with children. Overall, they are centred on the main following points: physical interaction and manipulation; physical-digital mappings; action-effect coupling; and meaning and level of abstraction of representations. In the lack of specific frameworks for tangibles and learning disabilities, such theoretical background is used in the present work as an overarching guide for the analysis of the data from the empirical studies.

Key examples of tangibles for learning

A large number of tangible systems in educational and related fields have been developed in the two last decades, an extensive review of which is out of the scope of this thesis. Systems presented in this section are considered key for being related with the four artefacts employed in the empirical studies of this research, namely: a tabletop, a system for making music, a set of interactive cubes, and a digitally augmented cylinder.

<u>Tangible tabletops</u>

Tabletops are a type face-to-face Single Display Groupware (SDG) that support multiple, co-located users interacting simultaneously through the same interface (Stewart, Bederson and Druin, 1999). Since the displays are limited in size, SDG systems tend to support small groups (typically two to four users), usually working together on the same task (Rick et al., 2009). Much research on tabletop technologies focuses on multi-touch interfaces (e.g. SenseTable (Patten et al., 2001), SmartSkin (Rekimoto, 2002) and DiamondTouch (Dietz and Leigh, 2001)). Recently, however, the implementation of tangible interfaces through tabletop surfaces has become more common as the kind of interaction they provide comes closer to traditional tabletop activities (Scott and Carpendale, 2006). Tangible tabletops combine interaction techniques of multi-touch surfaces and tangibles (Shaer and Hornecker, 2010).

A number of tangible interfaces have been developed that are based on tabletop surfaces with embedded tracking mechanisms: physical objects are placed and manipulated on planar surfaces, and their spatial arrangement and relations can be interpreted by the system. Examples include the previously cited Urp system (Figure 4.1) for urban planning, and, in the same domain, ColorTable (Maquil, Psik and Wagner, 2008), which provides means of envisioning urban change through co-construction of mixed-reality scenes. In a different field, SandScape and Illuminating Clay (Ishii et al., 2004) (Figure 4.6) are TUIs for designing and understanding landscapes where users can alter the form of a model by manipulating sand or clay and see the results via digital effects projected on the landscape model in real time.

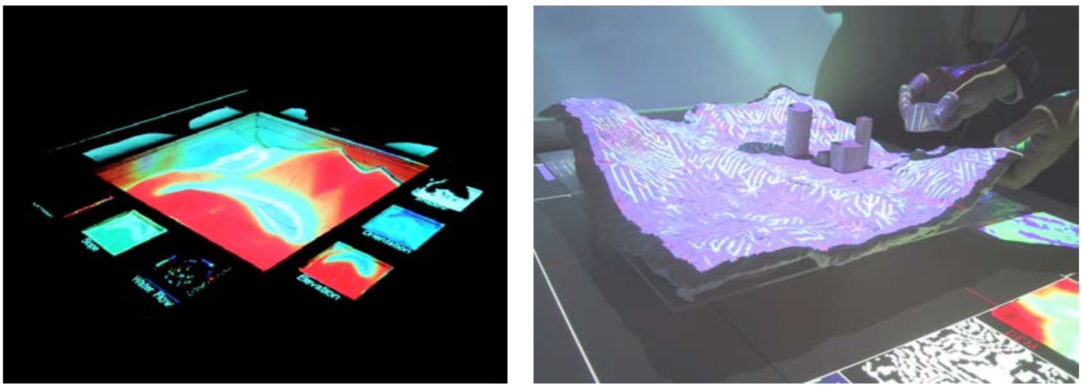


Figure 4.6: Sandscape (left) and Illuminating clay (right)
Source: (Ishii et al., 2004)

Another related system is Illuminating Light (Figure 4.7, left), which deals with concepts of optics - like the tabletop employed in the present research - but aimed for optical engineering students. The basics of interaction of both systems are quite similar, as users move physical representations of various elements on top of a workspace, and the system tracks these components and projects back onto the workspace surface a simulation of light propagation (Underkoffler and Ishii, 1998). The tabletop employed in the present research, however, was designed for teaching basic concepts of optics for children. The medium-scale prototype of Illuminating Light consists of a ceiling-mounted projector and coincident camera. Such machine-vision ceiling-mounted setup used to be a common implementation approach, but has among its main known drawbacks the occlusion caused by users' movements. The tabletop used in the present work was built ten years after Illuminating Light and is based on reacTIVision software for object recognition (Kaltenbrunner and Bencina, 2007), which overcame the occlusion issue. This technology builds on the success of reacTable (Jordà et al., 2007), a tabletop instrument for multi-user electronic musical performance where each physical device has a dedicated function, such as generating sound, filtering audio, or controlling sound parameters (Figure 4.7, right).

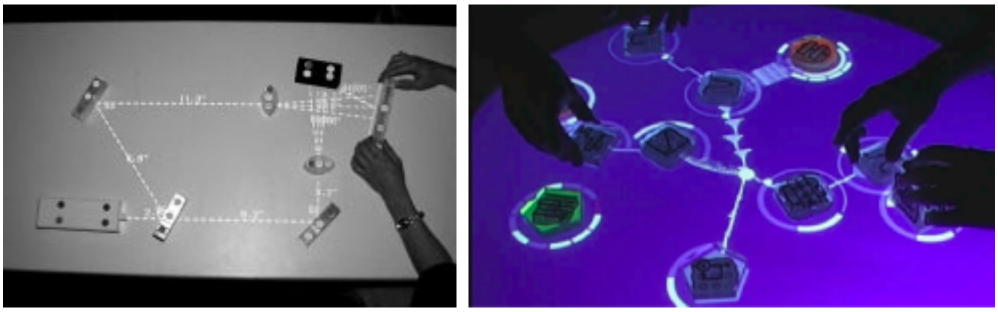


Figure 4.7: Illuminating Light (left) and reacTable (right)
Sources: (Underkoffler and Ishii, 1998) and (Jordà et al., 2007), respectively

A good amount of research has explored the benefits of tabletop displays for educational activities, such as encouraging group members to switch roles, explore more ideas and follow closely what each other is doing, and allowing those who speak little to contribute more through physical interaction (Rogers et al., 2008; Rogers and Lindley, 2004). Very little research to date explores how tabletop interfaces might be beneficial for populations with special educational needs. Roldán et al. (2011) proposed a system for dynamic adaptations of educational activities in multi-touch tabletops for people with Down syndrome, but no empirical findings are reported. Piper et al. (2006) designed Shared Interfaces to Develop Effective Social Skills (SIDES), running a tabletop application for adolescents with difficulties in social interaction (particularly Asperger's syndrome) to develop their social and group work skills. The application is a cooperative, multi-player digital game that encourages negotiation, turn taking, active listening, and perspective taking, increasing collaboration and decreasing competition. The authors report that during the sessions, the adolescents remained engaged in the activity the entire time, shared the responsibility and played collaboratively, which is unusual for people with Asperger's sydrome. The artefact's reliability and consistency in rule enforcement were found to be particularly useful for these adolescents, who prefer predictable environments (Piper et al., 2006). However, Piper's work, besides being based on multi-touch and not tangibility, is very much focused on addressing specific characteristics of autism. No studies were found on tangible tabletops and children with intellectual disabilities, as it is proposed in this thesis.

Musical applications

Musical applications are one of the oldest and most popular areas for TUIs. They can be designed for novice users, being intuitive and easily accessible, or for professionals looking for physical expressiveness, legibility and visibility when publicly performing (Shaer and Hornecker, 2010). Instruments such as the aforementioned reacTable (Jordà et al., 2007) are fully controllable sound generators or synthesizers. Another tangible music table that also interprets interactions with tangible devices on an interactive surface is AudioPad, where graphical information is projected on and around the physical devices to give the performer sophisticated control over the synthesis process (Patten, Recht and Ishii, 2002).

Other tangible musical artefacts have music 'contained' within a sensorized object, and different forms of interaction, like rubbing, squeezing, or plucking, trigger different replays. An example of this paradigm is the Squeezables (Weinberg and Gan, 2001), an instrument that allows a group of users to compose music by squeezing and pulling six gel balls mounted on a small podium (Figure 4.8, left). It provides 'organic'-feeling control and senses multiple axes of synchronous and continuous hand gestures.

Finally, a number of musical TUIs consist of building blocks that continuously generate or manipulate sound and can be stacked, attached, or placed in each other's vicinity (Shaer and Hornecker, 2010). Block Jam (Figure 4.8, right), for instance, consists of a set of cubes that can be attached to each other to control a dynamic polyrhythmic sequencer, which interprets the arrangement of the blocks as musical phrases (Newton-Dunn, Nakano and Gibson, 2003). Another example is AudioCubes, created to allow intuitive, dynamic exploration of changing sound. Sounds are created and manipulated by using cubes that communicate with each other and whose properties like location, movement and arrangement feed into a sound processing network (Schiettecatte and Vanderdonckt, 2008).

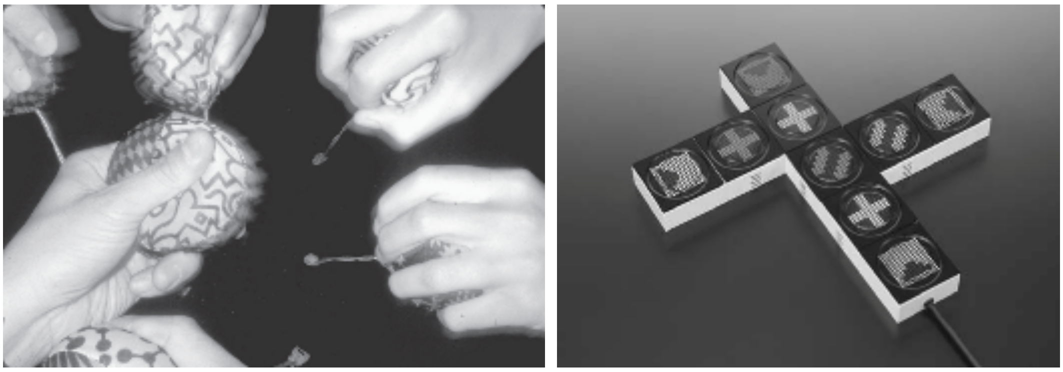


Figure 4.8: Squeezables (left) and Block Jam (right)
Sources: (Weinberg and Gan, 2001) and (Newton-Dunn, Nakano and Gibson, 2003), respectively

Most musical tangible applications share the goal of being engaging and interesting both for novice and experienced users, allowing people to express themselves through music in an intuitive and meaningful way provided by tangible interaction. However, the systems presented here were evaluated in rather informal studies, such as observing festival attendants interact with the artefacts, and most reports consist basically of anecdotal accounts of user engagement. Despite their potential as "expressive and enjoyable gates to deeper musical experiences" (Weinberg and Gan, 2001, p. 4), very little is available about the use of such musical systems in educational contexts for children. The musical tangible system employed in the present research (the d-touch drum machine) falls into a hybrid category, as it consists of a set of blocks that can be placed on a specific surface to manipulate sound, however there is no visual projection involved (see Chapter 7 for more details). Although the drum machine was not designed for children, it is also claimed to be intuitive for different levels of expertise. Using the drum machine, this thesis aimed to analyse the interaction of children with intellectual disabilities with applications that are mainly based on audio representations.

Digital manipulatives

Digital manipulatives can be considered computationally enhanced versions of physical objects, particularly referring to traditional educational manipulatives and children's toys (Resnick et al., 1998). Digital manipulatives are part of the embodied interfaces paradigm, integrating the physical body of the device with the virtual contents inside and the graphical display of the content (Fishkin et al., 2000). The direct embodiment of computational functionality can be considered a specialised type of tangible interface formed uniquely by one or more physical interaction objects (Shaer and Hornecker, 2010).

The Lifelong Kindergarten group[1] has developed a number of digital manipulatives. The Programmable Bricks consist of LEGO bricks with embedded computation to control motors and lights, and read information from light, touch, and temperature sensors. According to the authors, young children were able to explore concepts of feedback and control that are usually considered advanced. Another creation of the same group is the Programmable Beads (Figure 4.9, left), which allowed children to create dynamic patterns of light. Different beads had distinct functions, like: pass the light to the next bead, reflect light back, or stop the light. The beads allow children to explore ideas of decentralized systems and emergent phenomena (Resnick et al., 1998). SystemBlocks and FlowBlocks (Figure 4.9, right) are computationally enhanced building blocks that support learning of abstract concepts in domains like mathematics of change and probabilistic behaviour, by allowing the construction of generic structures (Zuckerman, Arida and Resnick, 2005).

[1] http://llk.media.mit.edu/

Figure 4.9: Programmable beads (left) and Flow Blocks (right)
Sources: (Resnick et al., 1998) and (Zuckerman, Arida and Resnick, 2005), respectively

All these digital manipulatives are examples of tangible programming kits, which aim to make programming more accessible for children by using physical objects to represent various programming elements instead of pictures and words on a computer screen (Horn and Jacob, 2007). Other examples of tangible programming kits include: Algoblock (Suzuki and Kato, 1995), in which aluminium blocks can be combined to represent the commands of a language similar to Logo; Electronic Blocks (Figure 4.10, left), which allow young children to build 'computer programs' by stacking blocks to create and control robots (Wyeth and Wyeth, 2001); and, in a different line of implementation, Tern (Figure 4.10, right), a language for controlling virtual robots on a computer screen that uses inexpensive and durable parts with no embedded electronics or power supplies, which are combined offline and then scanned on a portable station (Horn and Jacob, 2007).

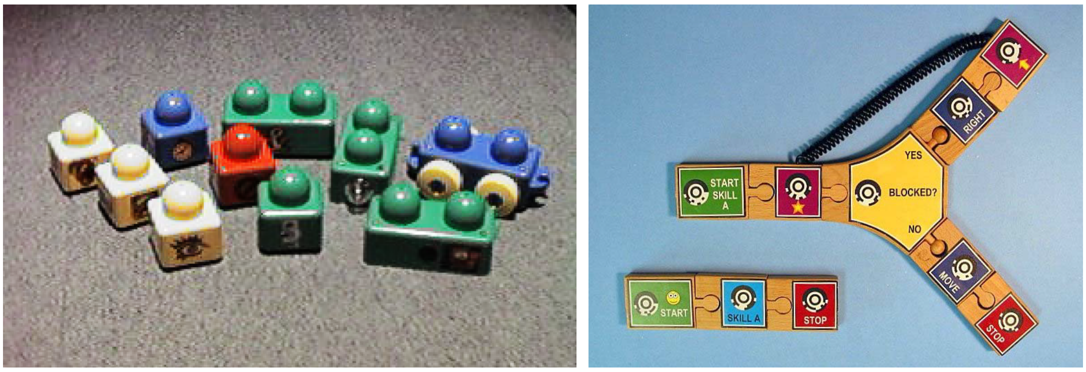


Figure 4.10: Electronic Blocks (left) and Tern (right)
Source: (Wyeth and Wyeth, 2001) and (Horn and Jacob, 2007), respectively

Such examples show the popularity of sets of physical blocks augmented with digital technology to become interactive and communicate with one another, in particular to teach basic concepts of logics and programming. However the particularities and benefits of tangible programming for children is not in the scope of this thesis. The set of blocks used in this research (the Sifteo cubes) allows exploring the benefits of the direct embodiment of computational functionality through the use of different applications with distinct goals and characteristics, but all based on interactivity and communication between blocks.

Taking a different approach, other digital manipulatives explore physical properties of objects. Smart Blocks, for instance, allow users to investigate aspects like volume and surface area of three-dimensional objects through physical manipulation, leveraging the benefits of physicality with the advantages of digital information (Girouard et al., 2007). Curlybot (Figure 4.11, left) is an autonomous two-wheeled vehicle with embedded electronics that follows the same principles of the aforementioned system Topobo (Figure 4.3). Curlybot can record how it was moved on a surface and then play back that motion repeatedly. According to the authors, children can use Curlybot to develop intuitions for advanced mathematical and computational concepts like differential geometry (Frei et al., 2000). BitBall (Figure 4.11, right) is a transparent, rubbery ball augmented with a programmable component, an accelerometer, and coloured LEDs. BitBall can be programmed to, for instance, turn its LEDs on based on the motion detected by the accelerometer. The authors believe that experience with BitBall helps students develop a physical understanding of acceleration that they can more easily transfer to new contexts and associate to the physical world (Resnick et al., 1998).

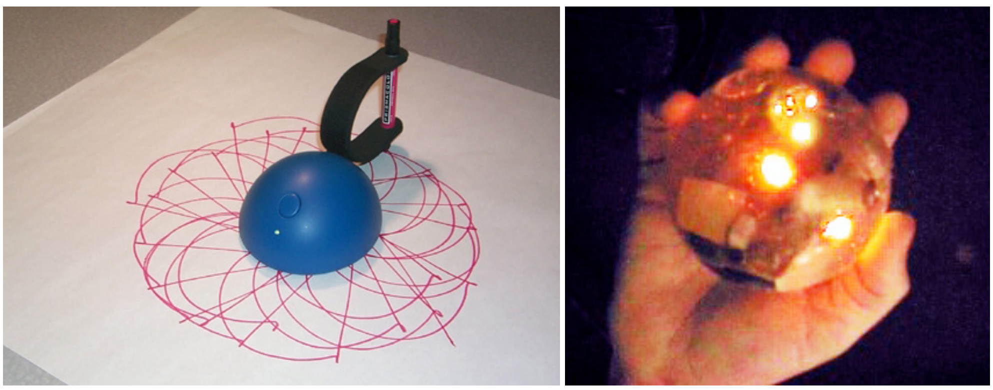


Figure 4.11: Curlybot (left) and BitBall (right)
Source: (Frei et al., 2000) and (Resnick et al., 1998), respectively

The augmented object used in the present research fits within this second approach of digital manipulatives, focusing on physical properties of the objects themselves. Similarly to BitBall, it is able to respond to movement to convey information. This thesis analyses how children with intellectual disabilities respond to such interaction.

Tangibles and special educational needs

Generally speaking, the use of digital technologies is seen as beneficial for students with special needs (Abbott, 2007). In the 1990's, Information and Communication Technologies (ICT) resources were reported as means of providing a zone of comfort and sense of control, with opportunities for SEN students to do things they would not do otherwise, like allowing the expression of their creativity through software resources, creating sense of achievement and improving concentration, motivation and self-esteem (DES, 1991; Hawkridge and Vincent, 1992). However, the dominant approach in schools for the use of technology with the special needs population remains 'drill and practice', which is also the main focus of commercial software for learning needs (Adapt-IT, 2009; Microsoft, 2012). Software packages such as Integrated Learning Systems (ILS) are popular, with literacy and numeracy activities in conjunction with diagnostic tools that aim to offer individually-tailored activities for the students' needs perceived by the system (Abbott, 2007; Anderson, Anderson and Cherup, 2009). Software programs like these, called 'tutor' or 'computer-assisted instruction', represent a longstanding type of educational technology, mostly based on the medical model of learning difficulties and cause-effect activities, advocated by behavioural learning theories (Abbott, 2007; Florian, 2004). Despite the popularity of such programs, government reports are decreasingly positive about their use, and researchers began to doubt their efficacy (Underwood, 1994). As the present research takes a socio-constructionist philosophical perspective on learning difficulties and follows the constructivist theory of learning, rather than adopting the medical model and behaviourist approach, drill and practice technologies are not investigated here.

With the advent of modern technologies, exploratory learning environments are being developed that aim at stimulating sensory engagement, collaborative learning, creativity and flexible thinking (Keay-Bright, 2008), aligned with constructivist and discovery learning theories. As aforementioned, tangibles are said to be a particularly accessible type of exploratory technology, partly due to their inherent intuitiveness and usability (Zaman et al., 2012), but also because of the multimodality of tangible interaction engaging multiple senses. People with learning disabilities are generally mentioned in the tangibles literature as a population that could particularly benefit from interaction with TUIs, as these are said to provide a richer learning environment with more opportunities for cognitive, linguistic and social learning than a traditional graphical user interface system (Shaer and Hornecker, 2010). Only recently, however, has specific research on TUIs for supporting learning of children with special educational needs started to emerge (Shaer and Hornecker, 2010; Zaman et al., 2012). Empirical studies reported in the literature so far have investigated two main themes: educational robotics and interactive assembly kits; and language and communication development, as discussed next.

The tangible assembly kit with kinetic memory Topobo (Figure 4.3) has been used in studies with children with different learning difficulties. Parkes et al. ran sessions with Topobo and children with Attention Deficit Hyperactivity Disorder (ADHD) and Asperger's syndrome. The authors reported that the children were immediately attracted by the artefact, were able to collaborate, and remained engaged for unusually long periods (around one hour), being focused as long as they were given guided tasks, such as small specific problems to solve with detailed instructions (Parkes, Raffle and Ishii, 2008). In another study by Virnes et al., eight children with mixed learning needs used Topobo and Lego Mindstorms over nine months. The authors derived several design challenges for educational robotics for special needs, related to five dimensions. For instance, for the dimension of 'Expressing', challenges include combining bricks from different construction kits and programming for different levels of difficulty. For the dimension of 'Exploring', the challenge is to give feedback mediated by different surfaces and materials, sounds, lights and movements. In the 'Two-way communication' dimension, a challenge is to give hints to guide development. The authors also suggest that programming should be done via physical manipulation (Virnes, Sutinen and Kärnä-Lin, 2008).

Finally, Farr et al. compared the activity of children on the autistic spectrum playing with Topobo and with conventional Lego blocks. The authors reported children's higher engagement in social activities (co-operative play, on-looking and parallel play) and less solitary behaviour when playing with the tangible (Farr, Yuill and Raffle, 2010). In the field of narrative and play, Farr also found more cooperative and less solitary play when children with autism interacted with a configurable narrative augmented Playmobil set (the 'Augmented Knights Castle'), and a non-configurable version of the same toy (Farr, Yuill and Hinske, 2012). In the configurable system, children could listen to characters' speech when placing them in different parts of the castle, but could also record their own voices and assign the recording to the Playmobil characters. Configurability was reported by the authors as a key factor for allowing greater individual control for children with autism. In addition, predictable and personal content playback created a quality experience for the children, and input of user content created more opportunities for interaction with peers (Farr, Yuill and Hinske, 2012).

Aiming at helping children with learning disabilities to communicate and learn abstract properties of physical objects, Cobb et al. developed Enlighten, a system that allows users to interact with displays and objects in the environment by shining ordinary torches over surfaces of interest (Cobb et al., 2006). The authors claim that Enlighten may help children with special needs to learn from and form links between physical objects and abstract information, as children can explore the physical environment with the torches and become exposed to digital information, plus digital media can be used to direct attention of children to specific aspects of the physical environment. Enlighten extends learning experiences offered by sensory rooms, for example with torch-activated sounds that help building cause-effect links and control aspects of the environment (e.g. when a torch is shone on a CD, the music played). Enlighten can also provide additional means of communication, as children can learn how to communicate their choices and needs by shining the torch onto photographs, objects, symbols and so on (using objects of reference to express their desires). The objects or symbolic representations can also have coupled sounds (e.g. 'car' and 'sound of engine running') and be associated to an activity (e.g. a wooden spoon representing cookery). The system encourages listening skills in children unable to read (shining the torch on a book would trigger the audio of the story). Enlighten was used by children with profound and multiple learning difficulties (PMLD), severe learning difficulties (SLD) and moderate learning difficulties (MLD). Children with PMLD and SLD had difficulties in manipulating the torch and pointing it accurately, establishing cause-effect links and mastering the choice-making strategy. Children with MLD presented a good control of the system and were able to discover information from pictures.

Also related to communication is 'LinguaBytes' (Figure 4.12), a tangible play-and-learn system for toddlers with multiple disabilities aimed at stimulating language and communication skills (Hengeveld et al., 2009). With LinguaBytes, children can play with interactive storybooks, place wooden toys on a wooden base to hear their names, solve interactive puzzles where the physical pieces relate to on-screen representations, build sentences by placing three cards on the base, among other activities. Hengeveld et al. found that children showed more initiative, with a longer attention span; physical interaction slowed down children's activity allowing more control over its timing; and slower interaction provided more opportunities for facial, gestural, and verbal expressions by the children.

Figure 4.12: The LinguaBytes system
Source: (Hengeveld et al., 2009)

Another example in the field of language development was designed by Garzotto and Bordogna and consists of a set of low-cost and customisable learning experiences that combine the visual communication paradigm of Augmented Alternative Communication (ACC) with multimedia tangible technology (Figure 4.13). Using the 'Talking Paper' application framework, teachers and therapists can associate paper cards, drawings and pictures to multimedia resources like sounds and animations, and customise playful interactive spaces to the specific learning needs of each child. The system aims at supporting cognitive, linguistic and motor development of severely disabled children in the school context. From a qualitative study with two children, the authors reported signs of engagement and enjoyment, increasing the self-esteem of children; improvement of linguistic and narrative capability, and of autonomy and motor control (Garzotto and Bordogna, 2010).

Figure 4.13: A scenario of the paper-based tangible system to support ACC
Source: (Garzotto and Bordogna, 2010)

As presented in this section, overall empirical research in tangibles and learning disabilities mainly reports: children's sustained engagement and attention; enjoyment and interest in the artefacts; higher levels of social behaviour and collaboration; need for guidance and hints; greater individual control over the interaction; and higher levels of initiative and autonomy. However, none of the research presented targeted children with intellectual disabilities nor specifically mapped the characteristics of tangible interaction to children's activities and reactions, as proposed by the present research.

Implications

Tangible technologies have a great potential as mediators of human activity, providing physical experience augmented with digital effects. By keeping the benefits of, on one hand, sensorial engagement, and on the other hand, interactivity and dynamics of digital technology, tangibles are expected to provide the best of both worlds and bridge the gap between the physical and the virtual. The paradigm of tangible interaction is in line with this research's theoretical foundations, being rooted in the well-known theories of embodied and distributed cognition, and having important implications in educational domains, where research with tangibles is increasingly gaining popularity.

Besides supporting constructivist learning through physical interaction, expectations are that the coupling between physical and digital worlds facilitates learning by providing clearer links between concrete and abstract representations, broadening comprehension of abstract concepts by situating them in real contexts open for exploration, and capitalising on the physical properties of objects.

Characteristics of tangible technologies make them particularly interesting for supporting learning of children with intellectual disabilities: physical interaction and multimodal sensorial engagement, concrete instances to support comprehension of abstract concepts, personalised and accessible learning, and links with real-life examples and situations, are strategies recommended to improve learning for these children (Chapter 2). In addition, the guidance given through digital feedback and by the objects' physical affordances can help structuring children's exploration within discovery learning activities, which is known to be problematic (Chapter 2) and is the focus of this thesis.

Nevertheless, expectations on tangibles giving effective support for the education of children with intellectual disabilities are only starting to be validated, as technology becomes more largely available and accessible. Traditionally, technologies for special needs aim at providing accessibility for physical impairments, or consist of behaviourist drill and practice software. Exploratory environments like tangible interfaces have timidly been investigated with this population, and so far, empirical studies have mainly indicated positive effects on engagement, collaboration and initiative, although most accounts remain anecdotal. Most of the more structured and solid results concerning tangibles and special needs focus on the specific population of children with autism, such as Farr's work on cooperative versus solitary play. Despite being important references for the present work, these findings concern specificities related to autism, play and social behaviour that are not in the scope of the research.

It is still to be investigated how and which characteristics of tangible technologies may support children with intellectual disabilities to productively engage in exploratory activities of discovery learning, overcoming difficulties like lack of structure and open-endedness. Having laid the theoretical foundations of this thesis' argument, and made the case for the potential of tangibles in such context, the present work next describes the methodology employed to investigate this research question.

Chapter 5 – Methodological choices and considerations

Research consists of enquiry to make known something about a field, which is currently unknown (Brown and Dowling, 1998). In the nineteenth century, one of the greatest problems of social sciences was to neutralise the influence of ethical and political interests of researchers, so as to attain the objective reality, or the 'truth', as in natural sciences. This 'unbiased discourse of reality' was a premise of the then dominant positivist perspective (Poupart, 1997). The 'best' data was the 'primary data', i.e. with the least influence from the researcher. In other words, research should be a receptive study where facts were strictly observed by an 'outsider' (Pires, 1997a). Nowadays, the dominant perspective, and the one adopted by this thesis, claims that, rather than being neutral, knowledge production should actually be guided by ethical principles, and aim to help humanity (Pires, 1997a). Rorty suggests substituting the 'desire for objectivity' by the 'desire of solidarity', i.e. instead of trying to ascertain if their views and findings correspond to the 'objective truth or reality', researchers should ask themselves if their views contribute to improving people's lives (Rorty, 1994). This is the main driver of the present research, which attempts to improve the lives of people with intellectual disabilities by indicating potential ways of facilitating their learning processes.

Current theories accept and deal with the involvement and influence of the researcher, who puts themself in the research to pick up on relevant issues and events. According to interpretivism, 'truth' differs from person to person, as it depends on what individuals see and experience, and on how they interpret events: apprehension of the world goes through selection and interpretation, linked to people's values (Laperrière, 1997b; Rubin and Rubin, 2005). This is also consistent with the philosophical perspective of constructionism discussed in Chapter 2, according to which meaning is not an absolute entity to be unveiled, but is constructed by people based on their context and cultural background (Crotty, 1998; Schwandt, 2003). More specifically, this means that researchers' previous knowledge, even if subconsciously, affect and inform the research (Dey, 1993), and research findings represent a combination of the understanding of the researcher and of those being researched. The researchers themselves are data-construction instruments, whose skills of listening, observing, and understanding are crucial (Rubin and Rubin, 2005). Any social research will have biases, created by the goals of the research (Laperrière, 1997b). This is not to say, however, that researchers should not seek a systematic knowledge of the empirically valid (Pires, 1997a). The researcher's choices, theoretical beliefs and values must be clearly stated to allow a proper contextualisation of the results. Scientific rigour is obtained through a solid link between theoretical interpretations and empirical data, provided by appropriate methodology (Laperrière, 1997b).

The present research follows an interpretivist epistemology and constructionist philosophical perspective, taking an inductive approach to develop explanations by moving from observations to theory (De Vaus, 1993). It is a descriptive and exploratory kind of research that aims to investigate the 'how' and 'why' of phenomena (Deslauriers and Kérisit, 1997). More specifically, it looks at ways in which the characteristics of tangible interaction may support children with intellectual disabilities to productively engage in a process of discovery learning. The research is qualitative in essence, although a complementary quantitative analysis was also performed in the second phase (Chapter 9).

Research design

Qualitative research does not aim to test variables, but to discover them through exploration and generation of hypotheses. To reach this goal, a qualitative approach, when contrasted with the structured format of quantitative methods, is rather fluid, evolving and dynamic, heavily based on serendipity and discovery (Corbin and Strauss, 2008). The object of investigation is constructed progressively and refined during research as it comes into contact with the empirical field and the data. Field study is not only undertaken to find answers, but also to find questions and unexpected aspects (Pires, 1997a; Rubin and Rubin, 2005). Consisting of an exploratory research to investigate the behaviour of children with intellectual disabilities in interacting with tangible technologies, and how such artefacts may support discovery learning, the present work is a good fit for a qualitative approach.

Although framed and guided by the research question, the work was open to unpredicted events, and concepts emerged from the empirical data. It aimed to learn more about children with intellectual disabilities, and about if and how their learning process can be improved through the use of tangible technologies. Research design was flexible, with a first phase informing the planning of the second, in a process of refinement of the object of research, as questions emerged from the field study. Design of exploratory intervention sessions in the second phase was flexible to account for serendipity and discovery.

The research consisted of two connected phases. In the first phase, in-context natural behaviour was observed (teachers and students were observed in their schools) and teachers were asked about their behaviour, what they do and think, and why (Günther, 2006). The goals of this phase were to familiarise the researcher with the target population and the general dynamics of their educational process as it happens in schools, and build a shared understanding of teachers' views and practical knowledge about students with special needs. Data constructed informed the design of the second phase, which was the core of the work and consisted of observing behaviour in artificial situations and predetermined tasks (Günther, 2006). Empirical sessions were run where children with intellectual disabilities used tangible technologies in discovery learning activities.

Phase I: the field research

The specific goals of Phase I were (i) to gain insights and general empirical knowledge about the target population (children with intellectual disabilities); and (ii) to learn about the context of schools; in order to be able to design and plan empirical studies (to specifically investigate the research question) whose format would be adequate for these children and whose specific objectives would be plausible for the context. In order to achieve these goals, two research methods were employed: interviews and observations. Such two methods are commonly used in conjunction, due to disparities between what people *say they do*, and what they *actually do* (Cohen and Manion, 1994; Corbin and Strauss, 2008). In addition, in many cases people are not consciously aware or are not able to articulate subtleties of their activities or of the interactions between themselves and others (Corbin and Strauss, 2008). Observation is a way of addressing this issue – however, in observing, the researcher may give meanings to what they see that might lead to misconceptions. Interviews in this case allow checking assumptions with the subjects. It is thus beneficial to combine observations with interviews (Corbin and Strauss, 2008), besides being a form of triangulation, i.e. employing two or more research methods to approach the same topic. Triangulation increases rigour of data constructed (Brown and Dowling, 1998).

Interviews

In the context of qualitative research, an interview generally consists of an extension of an ordinary two-person conversation, initiated and guided by the interviewer to gather research-relevant information (Cohen and Manion, 1994; Rubin and Rubin, 2005; Willis, 2008). When the goal is to elicit the points of view of the participants, as it was in the present research, interviews are considered indeed very efficient (Poupart, 1997). In general, open, flexible methods of interviewing are more adequate for research in educational technology, because they allow the interviewee to discuss topics of their own choice (Willis, 2008). Such flexible interviews are commonly known as 'semi-structured' or 'loosely structured'. They allow probing and going in depth into topics depending on their relevance (Cohen and Manion, 1994). A set of pre-determined, open-ended questions with no fixed order serve as a guide, but a lot of importance is given to unstructured explorations that emerge during the conversation (Aldridge and Levine, 2001). Specific objectives and kind of information sought should shape interview questions, while response mode is unstructured, with minimum restraint on answers (Cohen and Manion, 1994). Each semi-structured interview is unique, as researchers match their questions to what each interviewee knows and is willing to share, and follow up on the answers of each participant. A semi-structured interview usually involves more active listening than aggressive questioning (Rubin and Rubin, 2005). So, themes may emerge that were not predicted by the researcher: the interviewee will talk about what is important for *them*, and the interviewer will reach saturation of relevant themes (Poupart, 1997). This format of interviews also encourages cooperation and establishes rapport between the researcher and the participant (Cohen and Manion, 1994).

In this sense, in a semi-structured interview it is important, first of all, to gain the interviewee's trust. Research goals should be explained, to situate the person within the context and purpose of the conversation, and anonymity should be guaranteed. The researcher must assume a neutral attitude and establish empathy with the interviewee. To help the latter to feel more at ease, it is also important to pick the right time and place. All this aspects, when appropriately taken care of, will contribute to obtaining the interviewee's true collaboration, and have them take initiatives and get involved, making valuable spontaneous contributions. Last but not least, the impact of ways of registering must be considered. Taking notes is usually less intimidating for the participant, but the researcher risks of missing a lot of information. On the other hand, audio or video recording guarantee capturing all that is said, but may prevent the interviewee from giving valuable information, for fear of being exposed (Poupart, 1997).

Information about the world obtained through this method is mediated by the subjectivity of the interviewee, their feelings and perceptions. What the interviewee says must be interpreted as what they believe in/ are convinced of – which was precisely what the present research was looking for when asking teachers about school dynamics and SEN students. The goal was to understand teachers' views and beliefs on their own practices, particularly those that involved students with learning needs, rather than obtaining some high-fidelity depiction of 'reality' in schools. Although the focus of the research was on children with intellectual disabilities, teachers were chosen as informants for being the 'driving force' of the educational system, responsible for planning and giving classes, and choosing which materials to employ. They interact with the students on an everyday basis, and are responsible for a substantial part of the students' educational experience, besides knowing well about their needs and preferences.

Obviously, the researcher can have their own interpretation and critical look on the information elicited – it is only natural that researchers make cultural assumptions that influence what they ask and how they construe what they hear (Pires, 1997b; Rubin and Rubin, 2005). The interviewee is a representative of a group, a participant-observer of their society, who will give information based on which the researcher will try and interpret the context in question, understand experiences and reconstruct events in which they did not participate (Poupart, 1997; Rubin and Rubin, 2005). Thus, from a constructionist point of view, each informant will contribute with partial reconstructions of the context, which will be compiled for synthesis and re-reconstruction by the researcher (Poupart, 1997). Interpretive constructionist researchers try to sort through the experiences of different people as interpreted through the interviewee's cultural lenses and then weigh different versions to put together a single explanation, which should cover the shared meanings of some particular group, though recognising that each person has distinct interpretations of events (Rubin and Rubin, 2005). The aim here is thus to describe *people's experience of* aspects of the world (aligned with the theory of phenomenography), which is a complementary approach to describing *aspects of the world* (Marton, 1981).

<u>Observations</u>

Generally speaking, observing a phenomenon is at the core of scientific investigation. In social sciences, observation is the first condition for building knowledge (Jaccoud and Mayer, 1997). Action and behaviour of people are central aspects of inquiry, so a natural and obvious research technique consists of watching, recording and describing what they do, then analysing and interpreting the data (Robson, 2002). As in the case of the present research, observations are commonly used in an exploratory research phase, and in an unstructured form, to find out, in general lines, what is going on, and to gain insights. The driving force of observations are the research questions, although they should not place too rigorous constraints on what is observed, but allow room for unexpected facts (Robson, 2002). In Phase I of the research, field observations were employed in conjunction with semi-structured interviews. Teachers who were interviewed were also observed while teaching classes where SEN students were present. The aim was to enrich the data of teachers' accounts of SEN students by directly observing their interaction with these students.

This constituted 'direct observation', meaning that the researcher observed *in person* situations and behaviours of interest (Chapoulie, 1984; Robson, 2002). An immediate appeal of such method is that participants and their actions are studied in their 'natural context' (Dowling and Brown, 2010), i.e. there are less foreign aspects to interfere with people's behaviour than in artificial settings. Direct observation was performed because the intention was to capture aspects of school dynamics and teachers' and students' behaviours and interactions as they happen in everyday practice. Observations were informal (Corbin and Strauss, 2008; Dowling and Brown, 2010; Robson, 2002), based on research-significant incidents – e.g. what is happening, and what people are saying and doing. As it is impossible to capture everything, the theoretical concepts, questions, interests and orientations in the researcher's head will drive the note taking (Corbin and Strauss, 2008; Dowling and Brown, 2010). A balance is needed between observing and note taking. In this sense, qualitative observation is also an instance of qualitative analysis, as the researcher takes notes to record some - but not all - aspects of the situations observed (Jaccoud and Mayer, 1997). A descriptive observation generally includes narratives of space, actors, activities, objects, events, time, goals and feelings (Jaccoud and Mayer, 1997; Robson, 2002). A posterior phase then includes compilation, abstraction and organisation of data to produce a description of the setting (Dowling and Brown, 2010; Robson, 2002).

The level of participation of the researcher in the environment under observation usually is positioned along a varying continuum from complete non-participation to complete participation. However, the extremes of such continuum are problematic (Dowling and Brown, 2010). On the one hand, it is an illusion to think that, when undertaking overt research (i.e. where participants are aware of the researcher's activities), researchers can place themselves in the community completely unnoticed. It is only natural that some influence always occurs as a consequence of the presence of a foreigner in the setting. If the intention is to perform a mostly non-participant observation, the research design must be so that such influence is minimised. Jaccoud and Mayer (1997) classify non-participant observation as an instance of a 'passive model', meaning that the researcher observes the environment with minimal intervention and interference, making an attempt to remain neutral and as 'invisible' as possible. On the other hand, to become a 'true' participant, the outsider must learn to 'be' like the subjects, taking into consideration all legitimate performances and identities in question. This can also be considered very hard to achieve, as one cannot simply decide to 'be' someone different and easily be seen as such by the community (Dowling and Brown, 2010). The reason for undertaking complete participant observation is based on the assumption that the researcher can only understand the reality by participating, and almost 'becoming' one of the participants (Jaccoud and Mayer, 1997). However, it is more realistic to say that the participant-observer will take on a role, which can be an existing role in the community observed - representing an *attempt* to 'become' one of the subjects - or can be the actual role of a researcher (Dowling and Brown, 2010).

The interactional model (Jaccoud and Mayer, 1997) is an alternative adopted by the present research. It takes a constructivist perspective on the role of researcher, seeing them as *contributors* to the construction of the reality, but by taking their actual role of researcher and not by being 'like' the participants. In this case, the researcher's influence is not to be eradicated, but is seen as a known factor to be taken into account, and subjectivity becomes a contribution instead of an obstacle (Jaccoud and Mayer, 1997). The complexity of social realities prohibits analysis other than from a specific perspective - results from one's observations are thus necessarily partial (Laperrière, 1997b). In this research, the researcher, being present in the classroom, did not take initiatives to manipulate what happened or to interfere in the scene whatsoever, but was at times naturally involved in activities, through teachers' invitation. The researcher was also object of students' natural curiosity, and interacted with them when solicited. This helped to make the students more comfortable with the researcher's presence, and gradually move their attention back to the teacher. The researcher thus became an actor in the scene observed, playing her own role, and contributed to the construction of meanings, according to her theoretical orientation (Pires, 1997a). Observation was open to insights and emerging themes related to SEN students, with a disposition for learning and discovery. Being the focus of the present research, SEN students also represented the specific perspective for observing and note taking. In this sense, observations did not intend to describe the whole class dynamics, but focused on the class dynamics *in respect to these students*, i.e. their behaviour and needs, their participation in activities, their interaction with peers, and teachers' attitude towards them.

Phase II: the empirical studies

Phase II consisted of a series of qualitative empirical studies, designed according to the research question and the empirical knowledge about the target population constructed from the field in Phase I. Phase II represented the core of the empirical work, and narrowed the research down to specifically investigate the question of how tangible interaction may support children with intellectual disabilities to productively engage in discovery learning activities. Qualitative studies in Phase II were performed in a dedicated environment especially set up for the sessions, which consisted of children with intellectual disabilities undertaking exploratory activities using tangible technologies. The sessions were facilitated mainly by the researcher, and in few cases by teachers. The format of the sessions was determined by a combination of methodological and practical reasons. Four key methodological choices are discussed here: natural versus dedicated environment, facilitation, location and data records.

First of all, as the main goal was to investigate children's interaction using tangible technologies, which are not part of their current school environment, an artificial situation had to be created. Introducing such artefacts in the classes would have been valid to undertake a more holistic socio-cultural analysis considering activities performed in the subjects' natural environment, and how/if the new technologies would fit in. However, this approach possesses a much higher level of complexity, because: (i) teachers would have to be trained on dealing with the technologies and spend a considerable amount of time planning specific classes; (ii) the technologies in question would have to be made available for all participant schools - which was not feasible because three out of the four artefacts used were still at a prototype stage; (iii) school heads would have to reshape the syllabus to fit in a number of activities using these artefacts - which is very difficult to do in practice due to curriculum demands.

Such approach was thus out of the scope of the present research, and the approach adopted consisted of creating short sessions of children's interaction with technologies in artificial environments. The limitations of the approach are acknowledged, such as the novelty aspect of the situation and artefacts, the unfamiliar environment for the children, and the disconnection between the sessions and the children and teachers' natural environment. However, the research focuses on aspects of child-tangible interaction that bring innovation to the learning process, and the findings are restricted to criticising tangible technologies in terms of how/if their characteristics support the needs of children with intellectual disabilities, rather than in terms of the use of these technologies within the broader context of school environment and all the involved social rules and relationships.

A second aspect relates to the sessions' facilitation. A choice was made for researcher-facilitated sessions. While teacher facilitation may be more natural for students and decrease the artificiality of the situation, asking teachers to facilitate demands a much higher engagement on their part, and be very difficult to obtain. Teacher-facilitated sessions would mean that, once again, teachers would have to be trained to use the technologies and would have to understand very well the research goals and procedures to be followed in the sessions. This would also introduce the risk of not obtaining appropriate data for answering the research questions due to teachers' different choices of methods and approaches, or even forgetting what to do. Another option is to allow teachers to explore the technologies with the students as they saw fit, but again, this would represent different research, as the type of data constructed would not be necessarily directed to the research questions. So, once more the researcher acted as a contributor to data construction within an interactional model of research (Jaccoud and Mayer, 1997), in the role of facilitator, according to the research aims and theoretical framework.

Nevertheless, teachers were always present during the sessions, and at times they spontaneously engaged in some interaction with the students. They were not encouraged nor refrained from doing so. Facilitation followed procedures of coaching within a guided-discovery approach, i.e. observing and helping individuals as they attempt to perform a task (Brandt, Farmer and Buckmaster, 1993). This includes the techniques of directing learner attention, reminding of overlooked steps, providing hints and feedback, challenging and structuring ways to do things, and providing additional problematic situations. Within the context of discovery learning, guidance and advice were implicit and non-directive (Choi and Hannafin, 1995). The level of guidance was varied in the studies in order to assess its influence in the process of discovery for children with intellectual disabilities in tangible environments (results presented in Chapter 9).

A third point refers to the sessions' location. The main tangible artefact used in the investigation was a large interactive tabletop at prototype stage of development that could not be easily transported. For this reason, all sessions with the tabletop were run at the university, together with studies employing other tangible artefacts. In some cases, however, the more portable artefacts were taken to schools, where a dedicated room was set up for the study, in similar conditions to the laboratory. Records of all sessions were made through video.

Video recording

Video was used to enable posterior analysis of data by the researcher, who, although acting as a participant-observer in the sessions, could by no means capture and interpret details of children's interaction, in parallel with facilitating the activities and dealing with the systems' technical setup. With the rapid development and widespread availability of video technology in the recent years, many learning science research projects have been making substantial use of video recordings, with the belief that interactions between people, artefacts and environment offer insights into learning (Derry et al., 2010; Plowman and Stephen, 2008). Video technologies allow detailed recordings of facts and situations, and catch actions and processes that may be too fast or too complex for the human observer watching the situation develop in real time. Although some information is inevitably lost in the recording process, a situation captured in video is more detailed, complete and accurate than one that is uniquely observed, besides being available for interpretation and analysis at any posterior time (Derry et al., 2010; Flick, 2009; Knoblauch, Schnettler and Raab, 2006). In comparison with other data collection methods, video recording includes the non-verbal parts of interaction that are not captured through audio recording, allows registering real-time actions instead of having accounts of actions from a retrospective point of view as in interviews, and provides the opportunity of capturing more aspects and details than in observation with note taking, thus reducing the selectivity of data construction and broadening the possibilities of analysis (Flick, 2009). Video data is not primarily concerned with talk, but more generally with ways in which the production and interpretation of action relies upon spoken, bodily and material resources, i.e. how people orient bodily, grasp and manipulate artefacts, and articulate actions within their activities (Heath and Hindmarsh, 2002). The use of recorded data thus controls the limitations and fallibility of in person observation, providing some guarantee that analytic considerations will not arise from selective attention or recollection (Heritage, 1984). It was thus fundamental to keep a detailed record of the sessions so as to revisit the data and undertake deep qualitative analysis.

It was a premise of the present research that the spoken and bodily conduct of the participants was inseparable from and reflexively constituted material features of the environment. The focus of the investigation was physical interaction of children with intellectual disabilities with tangible technologies, i.e. the different actions performed *by the children with such artefacts*. Although talk was considered in the analysis, actual verbal utterances of the participants were in many cases rare, due to this population's difficulties in verbalising their thoughts and even in articulating words. Thus, a lot of the analysis had to rely on subjects' actions and bodily postures.

To conclude, there are some drawbacks to be noted when using cameras. A rather obvious one refers to the interference of the recording equipment on the behaviour of subjects, an influence commonly labelled 'reactivity' (Knoblauch, Schnettler and Raab, 2006). The researcher should try to make the process as discreet as possible so that the recording equipment does not dominate the social situation (Flick, 2009), and in order to minimise the length of the 'phase of habituation', after which the effect of video becomes negligible in most cases (Knoblauch, Schnettler and Raab, 2006). In the present research, the camera was kept fixed on a tripod, so as to drift away from children's attention. It worked in most cases, although some children sporadically turned their attention to the camera during the sessions and made faces at it for a while. On the other hand, children did not seem intimidated by being filmed.

Another important issue is the selectivity of the camera's focus: generally the researcher must make a choice between a narrow focus in good quality and detail but without much of the context of the situation, or a good panoramic view of the social situation but without details such as facial expressions. Such choice should be guided by the research questions, taking into account what is more important to capture in the situation in order to answer them (Flick, 2009). As in the present research the focus was on the children's interaction with specific equipment, and not on a broader, natural environment where the situation takes place, the camera's selectivity was less of an issue. The main interest was on children's body and hands manipulating the artefacts, which could generally be captured by a correctly positioned, fixed camera.

Data analysis

The field research (Phase I) and the laboratory study (Phase II) generated a large amount of data to be analysed, at distinct times within the research. During Phase I, audio data from interviews were transcribed, and field notes from observations were compiled and organised. The combination of these data was iteratively analysed and qualitatively coded to generate key inputs for the design of Phase II. Video data from Phase II were transcribed and analysed qualitatively and quantitatively.

Qualitative data analysis

In qualitative data analysis, the researcher draws on own experience and intuition, trying to see the world from the participants' perspective and make discoveries that will contribute to the development of empirical and theoretical knowledge (Corbin and Strauss, 2008; Deslauriers and Kérisit, 1997; Pires, 1997a). Qualitative data consists of representations, definitions of situations, opinions, words, meanings of actions, and so on. The qualitative researcher must organise the data within a broad descriptive and interpretative framework, based on structural elements and processes specific to the phenomenon under study, engaging in a dialogical movement between the problem and the findings (Deslauriers and Kérisit, 1997; Dowling and Brown, 2010). Generally speaking, the role of the researcher is to interpret concepts from the field and give them a scientific formulation (Deslauriers and Kérisit, 1997). To do this, the researcher selects facts, chooses concepts and interprets results, i.e. selects (and must do so) *some* aspects of the context, aware of the impossibility of covering everything. This is acceptable because not all aspects are of interest for a specific research (Pires, 1997a). To analyse data, researchers necessarily draw upon some sort of accumulated knowledge, even if not directly related to the topic under investigation (Dey, 1993). Some background (being it theoretical knowledge, immersion in the data or professional experience) is needed to identify significance in data and discern important connections between concepts (Corbin and Strauss, 2008). Findings are a product of data plus what the researcher brings to the analysis. Researchers must be aware of the subjectivity involved in data analysis to be able to acknowledge their own influence on interpretations made (Corbin and Strauss, 2008). In the present work, the researcher firstly engaged in a field study in the complex environment of schools - however, the researcher's focus of attention and criteria for selection were guided by the research questions, both in collection and analysis of data. Such process of selection was based on previous immersion in the literature from the area, as well as the researcher's practical experience with the target population both at professional and personal levels. In the laboratory study, the researcher focused more specifically on characteristics of tangible interaction and their relationship with the needs of children with intellectual disabilities. It is important to note that 'focusing' in this context by no means implies that the researcher was not open to unexpected facts and findings, but rather that conclusions were all related to the specific topic under investigation.

Besides being an interpretative act, qualitative analysis is a very dynamic process of generating, developing and verifying concepts, which includes brainstorming, trying out different ideas, eliminating some and expanding others, for extracting significant properties of the research objects (Corbin and

Strauss, 2008; Manning, 1982). Concepts, in this context, are the analyst's combined understanding of what is being described in the experiences, spoken words, actions, interactions, problems and issues expressed by different participants (Corbin and Strauss, 2008; Rubin and Rubin, 2005). In the present research, qualitative content analysis was performed in both phases. Through systematic examination to identify patterns and connections, concepts were grouped into categories that were refined through iterative analysis, until saturation, constructing a coherent and explanatory story from data (Corbin and Strauss, 2008; Laperrière, 1997a; Rubin and Rubin, 2005).

The grouping of similar concepts under conceptual categories is commonly performed through coding, which is a process of identifying and labelling concepts according to their properties and dimensions, by using a classificatory scheme. Coding raises 'raw data' to a conceptual level by mining it through analytical strategies (Corbin and Strauss, 2008). At a high-level, coding can be seen as a process of translation of participant responses and field observations to specific categories for the purpose of analysis (Cohen and Manion, 1994). Ideally, it should eventually produce a composite summary of contextualised themes (Laperrière, 1997a). In a coding process, categories are not rigid, and adapt to the data set. New incoming data may cause the emergence of new categories or the refinement of existing ones. When data does not modify concepts and categories any longer, coding has reached saturation (Laperrière, 1997a). The analytical categories and explanatory schemes of relationships between the facts observed add to the theory on the research topic in question, closing the gap between the problem and the findings to generate the highest level of explicitness and coherence possible (Deslauriers and Kérisit, 1997; Dowling and Brown, 2010). The specific theory and hypotheses are constructed as the research progresses, and the theory is adapted and refined to cover each new case found in the data (Deslauriers, 1997). This process is called 'analytical induction', which seeks in a small number of cases the essential characteristics (or constitutive properties) of research objects and generalises them, assuming that, *being essential, they must apply to similar cases* (Pires, 1997b). In this context, the theory and hypotheses are the goal rather than the starting point of the research - they are derived from the interaction between information and interpretation (Deslauriers, 1997). The process of analysis encompasses a constant confrontation between emergent and existing theories on the object of study, and, ideally, it should eventually reduce such confrontations to a central narrative (Laperrière, 1997a). In qualitative research, theories are not seen as 'correct' or 'incorrect' representations of facts, but rather versions of reality from a certain perspective (Flick, 2002).

In Phase I of the research, qualitative content analysis was performed on the text from field notes and interview transcripts, in order to identify themes and categories to inform and guide the design of the empirical studies in Phase II. The findings from this phase are presented in Chapter 6. In Phase II, a video analysis was undertaken, which raises another point. Video data is multimodal and thus very rich and complex when compared to text, containing information on several levels (e.g. speech and visual conduct, gesture, mimic expressions, representation of artefacts, structure of the environment, signs and symbols). More often than not, time and/or cost constraints make a detailed analysis of the full video prohibitive. Data was analysed according to meaningful 'chunks', identified in terms of causal, behavioural and thematic structures, and transcribed at a sufficient level of detail for the research aims (Jewitt, 2006). Transcription does not replace video recording as data, but provides a resource that allows the researcher to become more familiar with details of the participants' conduct, clarifying what is said and done, by whom and in what ways, and exploring potential relations between multimodal aspects of the interaction (Heath and Hindmarsh, 2002). A whole-to-part analytical inductive procedure was adopted to identify major events, transitions and themes (Derry et al., 2010).

A complementary quantitative analysis

Qualitative video analysis generated the main findings of the present research, defined as qualitative in essence. Quantification would not have allowed the researcher to communicate how tangible interaction unfolded in all its complexity (Derry et al., 2010), as it is presented in Chapter 8. However, such holistic qualitative analysis did not provide sufficient evidence for assessing and comparing the differences between the two levels of guidance adopted in the empirical sessions' facilitation. A complementary quantitative analysis was thus undertaken with this goal.

Despite their origins in distinct epistemologies qualitative and quantitative methods can be combined to overcome the limitations of both sides (Dowling and Brown, 2010; Flick, 2002). Chi (1997) discusses different manners of integrating qualitative and quantitative methods that vary slightly in terms of focus and procedure. A first option, seen by Chi as the most conservative, is to use qualitative data to help interpret the quantitative results. A second option consists in using the qualitative analysis for generating hypotheses that are then tested by experimental methods. A third way, presented by Chi as the most straightforward and widely used, is to take quantitative measures as a complement to qualitative aspects. In this case, the quantitative data serves as confirmation of the qualitative analyses and vice versa (Chi, 1997). Finally, the method introduced by Chi (1997) in their 'verbal analysis' and adopted in the present research, relies strictly on qualitative data, but analysis can be quantified. This means that the qualitative data is examined for impressions and trends, methods of coding are developed to capture those impressions, and the coding can be analysed quantitatively. Chi argues that this is a kind of analysis that quantifies qualitative coding, as opposed to the methods presented previously, that do not actually integrate quantitative and qualitative methods but mostly use them side-by-side (Chi, 1997).

A coding scheme was thus created based on the qualitative analysis of the video transcripts (Chapter 9). The transcripts were coded in their entirety and all occurrences of each code were counted for quantitative analysis. Cluster analysis was performed to validate the statistical significance of the quantitative results.

Sampling

Generally, empirical research is concerned with generalising local findings to a wider range of contexts (Dowling and Brown, 2010). Indeed, when analysing and seeking comprehension of some human phenomenon, there is usually a goal to obtain a minimally organised model of reference for similar phenomena in subsequent moments (Holanda, 2006). Qualitative research is often criticised for a lack of reliable generalisation of findings. A key aspect for generalisation is the choice of participants. The method for sampling the population of interest to select the research participants has a direct impact on the generalisation that can be made (Flick, 2002). Generally speaking, sampling means considering a small amount of something to clarify some general aspects of the problem, or give an idea or clarification about something with the help of elements that relate to it. The goal of sampling is to provide a basis for knowledge or questioning, beyond the 'individual unities' (Pires, 1997b). In a quantitative paradigm, sampling obeys rigorous statistic rules, in order to form representative samples that will allow statistically valid results. Qualitative research, however, focuses on the relationships between sample and research object more than on technical rules, and is not tied up to statistical techniques: a qualitative sample is not probabilistic (Pires, 1997b). Participants are chosen on the basis of their relevance to the phenomenon under investigation and the formulation of categories, and not on the basis of being representative in terms of populations (Laperrière, 1997a). Thus, the relevant question within the qualitative paradigm is not on the size of a sample that allows generalisation, but on the properties and processes that characterise the research object, and how such aspects can be extracted from it (Pires, 1997b). Erickson argues that the responsibility for judgment about generalisation is not the researcher's. In fact, the reader must examine the circumstances of the research to determine if and how the case fits the circumstances of their own situation (Erickson, 1986).

According to a socio-constructionist perspective and aiming to address the context of schools, children that contributed to this research were selected on the basis of being considered intellectually disabled by their schools. Although reasonably heterogeneous, this group shares common key characteristics and must be treated as a group by teachers in the learning process, thus possessing total relevance to the phenomenon investigated.

Ethical considerations

Research with human beings invariably involves ethical aspects that must be seriously taken into account. Ethical responsibility and scientific adequacy must go hand in hand in fieldwork research, and entering the field in particular demands careful negotiation to establish rapport and trust between the researcher and the subjects (Erickson, 1986). Basic ethical principles followed in the present research included obtaining informed consent from participants, and guaranteeing anonymity, confidentiality of information and the right to withdraw at any time (Dowling and Brown, 2010). The present research adhered to the BERA Professional Ethics Code, and was approved by the Research Ethics Committee of the Institute of Education before any kind of data collection was performed. In addition, the researcher underwent a Criminal Record Bureau check, as the research involved children.

Informed consent was obtained in the following way: schools administrators and teachers received an information letter plus an oral explanation given personally by the researcher about the research procedures and aims. Children were given oral explanations by the teachers and the researcher, and their parents received information leaflets. Distinct consent forms were signed by head teachers (authorising the researcher to observe classes in the school); teachers (authorising the information from their interviews to be used in the research); and parents of all children involved in the empirical studies (authorising their children to take part and their images to be used for academic purposes). All forms can be found in Appendix 1. Parents were asked to talk to their children about the research and only authorise their participation in case of mutual agreement. For children who could not grasp the meaning of participating in the research, parents took the decision of giving consent themselves.

No physical risks were involved in the participation of children, and psychological and social risks were minimised for the research was not to be reported locally, but only in academic venues. Reporting to a general scientific audience does not expose local people to risk (Erickson, 1986). Even so, anonymity was kept in all cases: pseudonyms were used for reporting findings, participants' faces were digitally blurred in published images, and school names were not revealed. All collected data were kept safely: one copy at the University, in locked drawers, and the other copy at the researcher's house. Thus, the only possible psychological risks concerned children's stress during the empirical studies' activities, despite all care taken to create a positive and comfortable environment for children. Special care had to be taken due to the specific characteristics of children with intellectual disabilities. In this sense, children that presented any kind of resistance were never forced into doing the activities, shy children were not forced to speak, and children were free to interrupt the sessions at any time. Teachers or assistants were always present during the sessions to make the children more confident in spite of the unfamiliar environment, and their help was key in making children as comfortable as possible.

The findings of the research will be made publicly available through the thesis and papers in conferences and scientific journals. No financial incentive was offered to participants. By taking part in the present research, children and teachers had the opportunity to get to know and interact with innovative technologies before they are made available to the public, besides contributing for developing artefacts that are aimed at their own benefit.

Implications

This chapter presented the methodological choices of this work, situated them within the theoretical debate on research paradigms, and showed why these methods are appropriate to address the proposed research question of how tangible technologies can support children with intellectual disabilities in a discovery learning context. Empirical studies in the field of tangibles have traditionally followed the methods generally used in HCI, as no specific methods for evaluating tangible interfaces have been developed so far. Methods in HCI that are being employed for analysing tangible technologies commonly include quantitative empirical laboratory studies, heuristic evaluations, and qualitative observation studies often based on video analysis and sometimes conducted in the field (Shaer and Hornecker, 2010). The present research falls in the latter category, being therefore in line with one of the trends of the area. More specifically, ethnographic-style observation and interaction analysis approaches, both adopted in the present research, have been very influential in the field of HCI. In particular, interaction analysis of video is said to be well suited for studying the use of tangibles, for it provides an integrated approach that allows the investigation of verbal and nonverbal behaviours and focuses on the role of physical objects (Shaer and Hornecker, 2010). As it is also the case of the present work, it is acknowledged in the literature of the field that studies using such qualitative methods tend to remain open to new aspects, and develop analysis criteria iteratively, based on the observed data, being only coarsely guided by loosely phrased hypotheses (Shaer and Hornecker, 2010). This is important to bear in mind, as although artefacts are designed with an expectation of their probable use, in practice people create and communicate unexpected meanings, incorporating the artefacts to their activities in surprising ways (Dourish, 2001). In the case of the present research, which aims to investigate the potential uses of innovative technologies by the target group of children with intellectual disabilities, it is crucial to be open to the variety of ways through which these children interact with the artefacts, so as to generate design guidelines and identify pros and cons of tangibles in this context.

Chapter 6 – Phase I: learning in the field

Phase I was designed to gain insights and empirical knowledge about children with special learning needs, and to learn about the context of schools. Findings from Phase I informed the design of the main empirical studies (Phase II), so that they were run in an adequate format to allow an agreeable and productive experience for the children and at the same time to obtain relevant data to answer the research question. In Phase I, interviews and field observations were performed, the details of which are given in the next sections. This chapter ends with the presentation of the findings from Phase I.

Participants

Recruiting teachers and getting access to schools is problematic, due to tight schedules and teachers' many obligations. Time is always short, and the researcher must be flexible to adapt to participants' conditions. The approach of opportunity sampling was adopted in this thesis, where participants are selected on the basis of availability and convenience (Pires, 1997b). Participants were found through previous school contacts of the researcher, and by searching for schools on the Internet in the area of London - UK, where the researcher was based. Opportunity sampling is not probabilistic, but this is not an issue for the validity of qualitative research (Pires, 1997b), as discussed in Chapter 5. The important aspect was to select participants who were relevant as informants within the context of the research. Thus, teachers were selected on the basis of their experience with SEN students, and observations were performed where at least one SEN student was present. An opportunity also arose to perform observations of SEN groups visiting the Science Museum. Two types of participants are detailed in Table 6.1: participant institutions (for observations) and participant teachers (for interviews). Schools and participants' names are not revealed for confidentiality reasons.

Institution	Observations	Interviews
School 1 (secondary special school)	3 different classes: Physical Education, Mathematics, Science General school observation (common areas)	1 teacher (Science)
School 2 (secondary mainstream school with included SEN students)	5 different classes: Science, (with 3 different teachers), Life skills, English	2 teachers (Science) 1 teacher (Learning Development Unit Coordinator)
(contact made directly with teachers)	-	1 teacher (primary mainstream) 1 teacher (primary / secondary; working mostly with SEN students) 4 SEN teachers
London Science Museum – Launchpad Gallery	Special schools visiting day	-

Table 6.1: Participants of Phase I

The variation in the characteristics of schools and teachers shown in Table 6.1 was purposeful, as the aim of the research was to get an idea of the relationships of teachers and SEN students, the views and attitudes of the teachers and the characteristics of the SEN students, both in special and in mainstream contexts. The focus of the research was not on the type of school, but rather on the different kinds of educational experiences lived by those students. The variation therefore enriched the research. On the other hand, a focus on science can be noted from the sample: a visit to the Science museum, and a predominance of science classes and teachers. Although this was not a premise of the research, and thus not a necessary criterion for selecting participants, it was an interesting area to investigate because the tangible artefacts to be used in Phase II were mostly related to science, which is also an area where discovery learning is a popular approach. As the research was explained to school heads and teachers, science teachers were naturally more interested, involved, and willing to participate.

Procedure

Ten teachers with experience with SEN students were interviewed and seven hours of observations were performed at two schools and a museum (Table

6.1). The detailed procedure for each method of data collection is presented next.

Interviews

Semi-structured interviews were chosen as data collection method so that data could be flexibly constructed through direct verbal interaction. Although the researcher had a set of open-ended questions to guide the conversation, there was a particular interest in gaining insight into teachers' perceptions of intellectual disabilities and sharing their opinions, accounts and stories. Open questions helped to keep the focus around the themes being investigated, while allowing flexibility to investigate further any interesting topics that came up during the interview. Questions invited opinions rather than factual answers, and the interviewee was encouraged to go in greater depth in topics of interest rather than being limited to providing direct answers. The following set of questions was used for guidance:

- Which are the main needs and difficulties of children with special educational needs from your point of view?
- What do you find difficult when you have children with special educational needs in your class?
- How do these children take part in classroom activities and work together with peers?
- How do typically developing children find working with SEN children?
- What do you think could help children with special educational needs in regular classes?
- Do you use physical materials in your classes? What do you think of them? How do children with special educational needs find them?
- Do you use technological resources in your classes? Which ones? What do you think of them? How do children with special educational needs find them?

Most teachers were interviewed at school, at break-time or after class, in a teachers’ room or other common area of the institution. Two teachers were interviewed out of school, at a neutral place of their choice. Interviews lasted for about thirty minutes, stopping when reaching saturation of relevant themes, and were audio-recorded for transcription and analysis. In order to minimise the effects of audio-recording, the researcher clarified her intention of seeking information to help her own understanding, with the ultimate goal of suggesting technologies for the schools' own benefit. This approach helped establishing rapport between the two parties and minimised factors like respondents' self-consciousness and desire to show themselves in a good light or please the researcher.

Observations

Observations took place in common areas of the schools and in classrooms, and helped to better understand general characteristics of children with learning difficulties. Although such characteristics were also investigated through interviews with teachers, observing the children themselves provided additional information and insights for the researcher. Observations were direct and based on a constructivist perspective where the researcher becomes a contributor of the situation, even if only by their presence. In classroom observation, the researcher sat at a corner of the room in silence, with paper and pen, and did not take initiatives to participate, but was at times involved by the teacher in group activities, or spoken to by curious students. In such situations the researcher interacted normally with the teacher and students, which helped to decrease any feeling of uneasiness around the presence of a foreigner in class. Since schools typically receive visitors, like evaluators, student teachers, and researchers, the presence of the researcher was not considered to be of concern.

Observations in common areas of the schools were opportunistic, performed during waiting times. The researcher took idle time in schools to observe the dynamics, wall signs and posters, and teachers and students' behaviour and informal interaction throughout the school day.

In addition, two hours of observation were also performed at the Launchpad gallery[2] of the Science Museum in London, when the gallery was open for visit of SEN groups exclusively. Launchpad has more than fifty interactive exhibits and demos, illustrating science concepts. The exhibits encourage children to ask

[2] http://www.sciencemuseum.org.uk/visitmuseum/galleries/launchpad.aspx

questions and make sense of the way things work. During the SEN day, children had the opportunity to interact with several interactive installations with the guidance of the museum's explainers. The SEN day at Launchpad was especially interesting for the present research for providing a unique opportunity to investigate how SEN children deal with such interactive technologies, and further inform the design of the empirical studies in Phase II. The gallery is aimed at 8- to 14-year-olds, being thus in the scope of the research. The researcher was given formal consent to freely circulate in the gallery during the visit, and took notes on children's behaviour, kinds of questions asked, attention paid to explanations, and interaction with the exhibits.

All observations performed were qualitative and informal, registered exclusively through unstructured note taking guided by the research questions, which suited the exploratory nature of the research. Although the influence of the researcher's objectives constrains the resulting account, it fits with the aim of the research of eliciting aspects related to specific topics, rather than having a complete picture of all kinds of aspects involved in school classes. Observations mainly focused on: children's behaviour, kinds of questions asked, level of participation in activities, group work, social interaction, ways teacher addressed the children, and materials used.

Data analysis and findings

For qualitative analysis, accounts of the teachers and observations were compiled and interpreted to identify shared meanings about SEN students. In the process of analysis, notes from observations were re-written into a more structured narrative, and interviews were literally transcribed. In both cases, content analysis was performed through qualitative coding, following a general process of identifying meanings relevant for research, eliminating redundancies and forming clustered units, generating themed clusters, and contextualising the themes, through analytical induction. Through this process, conceptions of reality can be transformed into a stable set of categories of description, which, from the perspective of phenomenography compile "statements-about-perceived-reality" (Marton, 1981). The first pass of coding generated the following six broad categories:

- Students’ difficulties
- Students’ needs and preferences
- Teachers’ strategies
- Teachers’ difficulties
- Problems with educational materials
- Teachers’ goals for students
- Students’ positive characteristics

Tables 6.2 to 6.8 present subcategories under each of these categories.

Students’ difficulties	
Delay in learning	- Slower academic process - Unable to follow regular curriculum
Processing disorders	- Lack of concentration (easily off-task) - Difficulties with listening skills - Longer processing time and thinking time
Processing instructions	- Remembering verbal instructions - Accessing written instructions - Concentrating to listen to instructions (auditory delivery) - Recognising and retaining relevant information
Literacy	- Literacy underpins all areas of curriculum - Students struggle with written instructions - Such barrier generates negative feelings - Such barrier reinforces what students cannot do
Social skills	- Disagreements between students - Lack of understanding of others’ difficulties - Changing and falling out of friendships - Students considered weird by others - Difficulties to form pairs or groups - Reluctance to share - Preference for individual work - Ill behaving
Dealing with emotions	- Self-consciousness - Feeling of exclusion - Lack of maturity - Facing prejudice - Lack of self-confidence - Fear of making mistakes - Negative outlook on school and learning - Easily frustrated
Over-reliance on others	- High demand of teacher's attention - Things done for them
Physical engagement	- Problems with motor coordination - Not making sensible use of physical resources

Table 6.2: Subcategories for ‘Students’ difficulties’

Students' needs and preferences	
Kinaesthetic approach	- Physical engagement / use of the body - Practical activities - Visual representations - Resources to help students communicate, express themselves and interact
Meaningful contexts	- Real life situations - Practical applications
Structure of activities	- Routine - Repetition - Step-by-step activities - Instructions
Attainable challenges	- Short tasks / short-term achievements - Feeling of success and progress / rewards - Realistic targets - Keeping motivation
ICT	- Use of specific software (voice activated, screen readers) - Improving attention, perception and logical reasoning - Stimulating different senses - Students producing work independently - Clear action-effect links
Games	- Involving other students in supporting or learning roles - Reinforcing learning - Multisensory games to challenge students' senses

Table 6.3: Subcategories for 'Students' needs and preferences'

Teachers' strategies	
Present work in different / creative ways	- Use physical resources - Favour pictures and drawings over text - Perform practical activities - Use gestures and actions
Use ICT	- Use specific software for special needs - Use generic software - Use other tools like digital cameras - Interactive whiteboard with dynamic visualisations
Appreciate students' limitations	- Make concessions according to students' difficulties - Treat mistakes as natural - Ensure students learn the basics - Provide access for all and extra information for the more able - Set individual targets / Adapt to various levels of ability
Overcome barrier of literacy	- Ask questions students can answer verbally - Picking out information rather than detailed reading - Read things out for students - Help students to read by prompting words - Focus on keywords - Limited amount of writing

Encourage collaboration	- Teach social interaction - Mixed groups with peers as role models - Peer support
Increase independence	- Protect less and trust more the students - Stimulate and provoke students - Increase confidence - Stimulate participation - Give students roles and responsibilities
Create positive feelings and environment	- Establish good relationships in the classroom - Increase self-esteem - Decrease fear of making mistakes / use good humour - Value students' ambitions and dreams - Avoid labelling

Table 6.4: Subcategories for 'Teachers' strategies'

Teachers' difficulties	
Overcome barrier of literacy	
Deliver instructions	
Differentiate between levels of ability / types of needs	
Make children work together	- Manage social problems - Make children understand others' difficulties
Multisensory approach	- Dealing with large groups - Students' over-excitement and off-task
Finding materials students can access	- Lack of resources for individual work - Lack of resources for special needs
Training	- Lack of teacher training and support from the school - Reluctance to have more knowledge about SEN, to avoid more work

Table 6.5: Subcategories for 'Teachers' difficulties'

Problems with educational materials
Issues on safety
Lack of robustness
Usability / ease of use
Excess of written language
Lack of adequate challenge
Need for adaptation

Table 6.6: Subcategories for 'Problems with educational materials'

Teachers' goals for students
Students to learn to a maximum capacity for the longest possible time
Students to make maximum progress, achieve their best
Ensure everyone is able to achieve something
Ensure everyone has opportunity to participate
Prepare children for life outside school
Make children confident with equipment

Table 6.7: Subcategories for 'Teachers' goals for students'

Students' positive characteristics
Happy and proud to be assigned roles and responsibilities
Try to give their best
Feel very proud and smart when they get something right
Do not want to be treated as stupid or as young children
Enjoy talking about themselves to people with whom they feel comfortable
Like showing their work when they are proud of it

Table 6.8: Subcategories for 'Students' positive characteristics'

Findings from Phase I reinforced and complemented the literature in the area of SEN. Students' difficulties identified in the field research are consistent with problems commonly reported and discussed in Chapter 2, such as: being distractible and off-task due to difficulties in forming attentional strategies; over-reliance on external cues and people; reluctance to use own judgment and reasoning; low self-esteem and low academic self-concept, challenging behaviour; difficulties to adjust socially; difficulties in understanding instructions and remembering what has been taught; and the need for concrete examples. Similarly, teachers' strategies for dealing with SEN students also matched the literature discussed in Chapter 2: undertaking practical activities within a multisensory approach; using resource materials like visual aids and computers; going at the child's pace and ensuring tasks are in the child's capability; focusing on oral language and social skills; repeating, praising and encouraging to build confidence; and keeping tasks short and varied. In more general terms, the preference for hands-on learning and physical interaction with phenomena, along with relationships with students' real-life situations, as advocated in the literature, sprang from the data.

Drawbacks of poorly structured activities, lack of students' confidence and initiative, and high demands on teachers' time and attention within the context of discovery learning were also reinforced by the findings. Finally, regarding digital technologies, the predominance of drill and practice software and integrated learning systems for SEN, and the lack of suitable exploratory artefacts, as pointed out in the literature, were confirmed. Despite teachers' appreciation of students' enthusiasm for and the potential advantages of digital technologies, there is a remarkable lack of artefacts that can be productively used for the SEN population, as pointed out by different subcategories in Tables 6.3 to 6.6.

The first pass of data analysis also provided important additional findings that complement the literature: general goals teachers have for their SEN students; more specific teaching strategies and attitudes towards the students; uses teachers make of technologies; deficiencies such technologies present for the SEN context; and positive characteristics of SEN students. However, as Tables 6.1 to 6.8 show, this first pass of analysis produced a large number of subcategories and inter-related topics. Such data corpus presented some redundancies and conflicts. Redundancies can be found for instance in overlaps between the categories of teachers' strategies and students' needs, as the former naturally addresses the latter. Similarly, teachers' difficulties are deeply related to students' difficulties, i.e. teachers struggle to find ways to overcome students' difficulties. Examples of conflicts include students' strong need for kinaesthetic approaches versus their difficulties with physical engagement, such as motor coordination and over-excitement leading to poor concentration. Another example of conflict is keeping tasks highly guided and structured while still stimulating students' independence.

Different directions could have been adopted for eliminating redundancies, resolving conflicts and producing a more coherent and cohesive data set in a second pass of analysis. In this thesis, the analysis was narrowed down to aspects that were relevant to the specific aim of Phase I, which was to frame and inform the design of the main empirical studies consisting of exploratory sessions where children with learning disabilities interact with tangible technologies. In this sense, two broad categories were created that grouped relevant topics for the context of the research: aspects that could potentially be addressed by the final outcomes of the present research, and aspects to be taken into consideration for the actual design of the empirical sessions. These aspects are presented next in a narrative form, directly constructed from the topics presented in Tables 6.1 to 6.8.

Opportunity for intervention

Findings have shown that there is a need for more educational resources that are adequate and accessible for children with learning difficulties, to help them understand, communicate and express themselves, interact with others and work more independently. A kinaesthetic approach is recommended and adopted by the teachers, with resources and activities creating opportunities for physical engagement, i.e. doing things, touching, manipulating and moving, as demonstrated by the following interview quotes:

> *"If they* [the students] *can see and feel it, a model they can touch, they understand it better than just being told about it, or writing about it."*
>
> *"Students learn best when there is either a visualisation or an actual physical activity. They often consolidate their learning a lot better."*
>
> *"The more physical resources that we have the more likely it is that learning will be consolidated. Most of our students learn best when it's either visual or tactile, something they can actually see or do."*
>
> *"With concrete materials, we can simulate real-life situations and experiences they developed inside themselves, in their lives. It is important for them to touch things, experience them. We can take advantage of the abilities of each student. Dealing only with abstract is much more difficult."*

Resources must thus create alternatives for presenting information and producing knowledge, preferably focusing on oral interaction, with dynamic visualisations and a limited amount of writing. Differentiation between levels of ability and types of needs is a challenge, and the resources should provide different activities to account for a number of levels and needs and ensure everyone has opportunity to participate. Resources should also allow group work and encourage collaboration, so that peers can give support to one another, and there is opportunity to observe others as well as for individual expression.

The proposal of the present research of using tangibles with children with intellectual disabilities is backed up by these findings, as they support the theoretical hypothesis that a combination of physical engagement and dynamic visualisations would be beneficial for these students. Teachers do believe that technology brings advantages for the students:

> *"They* [the students] *really enjoy those lessons* [with ICT]*. They love it."*

> *"Technology is a way of stimulating through different senses in a dynamic way."*

However they point to a lack of adequate educational resources for children with special needs, which need to be safe and robust, and provide forms of interaction beyond text-based. Data showed that common current uses of ICT in schools, such as information search on the web and preparation of slide presentations, are considered difficult and in many cases inaccessible for children with learning difficulties. Teachers highlighted the need for providing more challenges than simply drag-and-drop and copy-and-paste activities, as shown by the quotes below:

> *"I don't tend to use PowerPoint, unless I want to show them pictures."*

> *"The difficult part is to find something that they can access, because most websites have loads of writing. They find it difficult. So it is more or less getting them to download pictures or copy and paste pictures, so it's quite basic."*

Tangible technologies can provide support to such requirements for educational resources. Engaging in tangible interaction usually means moving objects around, and spatial qualities regarding the positioning of objects and their relation to the body are fundamental. This creates a multi-sensory experience, which not only offers a kinaesthetic interaction, allowing bodily engagement and manipulation of physical artefacts, but also provides a variety of modes of representation. Generally speaking, in tangible interaction, graphical representations and auditory and haptic feedback prevail over text, making them more accessible for children with learning difficulties. In addition, the possibility of sharing physical artefacts within an open and flexible environment invites for collective interaction, promoting collaboration. This is not easily achieved with personal computers, which are designed for individual use.

Tangibles also promote exploratory interaction, which should be flexible enough to accommodate different levels of achievement, allowing all to participate according to their own ability.

> *"You wanna treat them all equally, but it's the cruel realisation that everyone is different."*

To sum up, tangibles seem to have a good potential for supporting children with learning difficulties. Data constructed served as important empirical argument for proceeding with the research, to specifically investigate how the characteristics of tangibles may give support for children with intellectual disabilities in educational activities.

Informing the design of the empirical sessions

A number of aspects derived from the literature and from the fieldwork should be taken into account when designing the empirical sessions that aim to investigate how tangibles can support children with intellectual disabilities in discovery learning activities. Such aspects can determine design choices (e.g. challenges with short-term success) and the researcher's attitudes and behaviour in the sessions with the children.

First of all, tasks should be short, students should be aware of what is going to happen and reasons for doing activities should be clear. Preferably, activities should be contextualised and related to students' life. When possible, students should be involved in decisions, and be given roles and responsibilities. Concessions must be made according to their difficulties, and their limitations should be appreciated. Attention should be drawn away from their difficulties, mistakes should be given little importance, and good work should be acknowledged. Students should be stimulated and encouraged to do things themselves. Challenges should be attainable to allow short-term success and progress.

> *"If you can make sure that whatever your set, even the lowest one is going to achieve some of it, so they can see themselves moving on."*

It is important to be aware of emotional and behavioural difficulties that may arise: children with difficulties are easily upset/ annoyed by peers and easily frustrated when they cannot do the activities. They can be very shy and intimidated when out of their comfort zone, and give up when faced with difficulties, finding excuses to avoid activities.

> *"They become so self-conscious that they won't even speak or offer an answer because, you know, they're gonna get it wrong."*
>
> *"(...) and their self-esteem of being in a group where people can put their hand up and answer just like that, and they haven't even grasped what's going on."*
>
> *"They are a low-ability set and they know that, so there's a whole self-esteem issue as well going on there."*

When it comes to physical engagement, students are eager to touch, move and manipulate objects, but this may lead to over-excitement and distraction. Students easily engage in off-task activities and may not listen to explanations and instructions, and thus not reflect about the learning concepts. They may also present problems with motor coordination. In general it is important to look students in the eyes, call them by their names and speak loudly, slowly and clearly. It is also very important to create a positive environment, demonstrating interest in students' lives and stories, praising constantly with enthusiasm, and dealing with mistakes with good humour to avoid students' embarrassment. Such aspects are crucial for facilitating the sessions with the children and for levelling expectations as to students' performance and behaviour, being also fundamental to help create an adequate environment for the children, and avoid (or at least anticipate) major problems during the sessions.

Last but not least, the level of guidance usually demanded in exploratory activities with students with learning needs raised a specific research question that played an important role in the design of the empirical sessions. Children with intellectual difficulties are usually given a clear, well-defined, structured task, accompanied by close and detailed guidance (a lot of teacher talk, suggestions and step-by-step instructions), to avoid them getting distracted and lost in the activity. Students over-rely on others and are used to having things done for them, thus lacking independence and asking a lot of the teacher's attention. Findings revealed that the usual level of guidance received by children with special needs in school activities is extremely high, posing great demands on teachers and at the same time increasing students' over-reliance. This shows that if on one hand teachers mention students' over-reliance on others as a negative characteristic that could be addressed by stimulating initiative and independence, on the other hand they implicitly encourage students' dependent attitudes by making them used to very close guidance in activities, where they are literally 'taken by the hand'.

> *"We can't say that a certain student doesn't learn. Every creature in the world learns, they just need to be stimulated, sometimes in different ways."*
>
> *"They have to be stimulated and provoked, and we need to give them some independence."*
>
> *"They find it hard to learn everyday life activities. This makes the child dependent and seen as 'a poor thing'."*

One reason for teachers' conflicting attitudes may be the lack of appropriate educational resources for this population. In other words, with the current resources available, teachers may not see other ways of conducting productive exploratory activities with children with intellectual disabilities, than providing a high level of guidance and interference. Based on the common association between hands-on activities and discovery learning presented in the literature, and the difficulties faced by children with intellectual disabilities for whom the hands-on is recommended but exploration is hard, the present research aimed, from its start, to investigate better ways of supporting unstructured, discovery activities. The interesting paradox identified in the fieldwork regarding the choice of the level of guidance given to children with intellectual disabilities was reflected on the design of the empirical sessions, where the level of guidance by the facilitator was varied, so as to analyse the different results this had, in terms of students' interaction.

Implications

Research design, being qualitative, was inherently flexible and dynamic. Phase I was performed aiming at framing and feeding into the design of the main empirical studies. This was done through interviews with teachers who had experience with SEN students, and observation of classes where at least one student with intellectual disabilities was present. Qualitative, iterative analysis of such data revealed two broad categories of relevance within the context of the research and the aim of Phase I: opportunities for intervention, and recommendations for the empirical sessions. Within the perspective of phenomenography, data constructed in this process are categories of description that compile people's conceptions of the world, which here translate to teachers' ideas about and experiences with students with special needs. Such findings complement reports of the literature about these students, providing additional details about teacher's opinions and strategies, and, more specifically, current uses of technologies in schools.

Opportunities for intervention were identified in terms of tangible technologies filling the current need for exploratory artefacts that are accessible and challenging for students with special needs. Generally speaking, artefacts should: focus on oral interaction, with dynamic visualisations and a limited amount of text; provide activities in different levels of complexity; and allow group work. A priori, from the definition of tangible technologies, they can fulfil these aspects. Based on this general assumption, a thorough analysis was performed in Phase II that provided specific guidelines for the design of tangible artefacts for intellectually disabled students and facilitation of educational activities in this context.

Secondly, a series of recommendations was compiled to help designing the empirical studies with students with intellectual disabilities using tangible technologies, in terms of attitude and behaviour of the facilitator; students' behaviour; length of tasks; recommended practices, and particularly level of guidance offered to the children during the activities. Such recommendations can be summarised as follows:

- Keep tasks short
- Let students know what is going on and why they are involved
- Contextualise activities in relation to students' life
- Create a positive environment, showing interest in students' life
- Acknowledge good work
- Appreciate students' limitations and make concessions
- Set attainable challenges
- Beware of emotional and behavioural difficulties
- Give students responsibilities
- Stimulate and encourage independent actions and decisions

- Balance guidance and independence

The next chapter presents in detail the procedure followed in Phase II, including how the aspects derived in Phase I built into the research design.

Chapter 7 – Phase II: investigating tangible interaction

Phase II comprised the main empirical studies of the thesis. It was designed to investigate the research question of how tangible interaction can support children with intellectual disabilities productively engage in discovery learning. Phase II was designed taking into account findings from Phase I, as described in the previous chapter, and the literature of the area. Empirical studies consisted of facilitated sessions where children with intellectual disabilities used tangible technologies in exploratory activities. This chapter gives details on the tangibles used, the profile of the participants, and the procedures followed to run the studies.

The four tangible artefacts

The tangible systems employed in the studies were chosen according to two main criteria: design characteristics and availability. Children's difficulties did not inform the choice of the systems - instead, the artefacts were chosen seeking to cover the broadest possible range (considering the practical limitations of the research) of design aspects of tangible technologies. Such characteristics, derived from the literature as fundamental aspects of tangible technologies, are discussed throughout this section and summarised in Table 7.1, and mainly concern types of digital representations, distance between interaction and conceptual objects, and space-multiplexing. Choosing the systems according to their design characteristics and not according to children's needs can be justified by (i) the lack of tangible systems developed so far to address intellectual disabilities (see Chapter 4); (ii) the investigative nature of the research, which aimed to discover which characteristics of tangibles could be beneficial for children with intellectual disabilities. A second criterion was availability: as detailed next, the researcher had free access to the interactive tabletop and the augmented object for having been involved in their development; the d-touch drum machine could be downloaded from the Internet and easily built; and the Sifteo cubes were commercially available. The tabletop and the augmented object were designed for children within a similar age range as the participants of the present research (around 11 - 13 years). The Sifteo cubes are designed for all ages, although they have a higher appeal and a bigger number of available applications for children and adolescents. The drum machine is also designed for all ages, but its interface is not especially directed to children, as described later. Overall, users of all ages and abilities could interact with the systems, although they would reach different levels of comprehension for such interaction.

The interactive tangible tabletop

The tangible tabletop was designed as part of the Designing Tangibles for Learning project (2008 – 2010), at the London Knowledge Lab[3], to support young students learning about the behaviour of light, in particular basic concepts of reflection, transmission, absorption and refraction of light, and derived concepts of colour. With some adaptations, the setup of the tangible tabletop is fairly similar to reacTable's (Figure 4.7), using similar technology for object recognition. The frosted glass surface is illuminated by infrared LEDs, which enable an infrared camera, positioned underneath the table (Figure 7.1), to track the objects placed on the table surface, through the reacTIVision software. Such setup eliminates problems with occlusion and provides a more compact and portable system than with ceiling mounted apparatus (for more technical details see (Sheridan et al., 2009)).

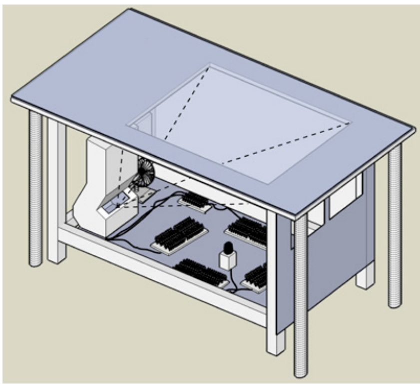


Figure 7.1: Schematic of the tangible tabletop
Source: (Sheridan et al., 2009)

[3] The author of this thesis worked in the Designing Tangibles for Learning project as a research officer, participating in the design of the tangible tabletop and the augmented object and the empirical studies performed. The present thesis, though also making use of such artefacts, has a different aim from the project as it focuses on children with intellectual disabilities.

The objects that serve as physical interaction devices are handcrafted and off-the-shelf plastic objects (Figure 7.2). Individual object recognition, including location and orientation, is enabled through paper marker tags known as 'fiducials' (Figure 7.2, right).

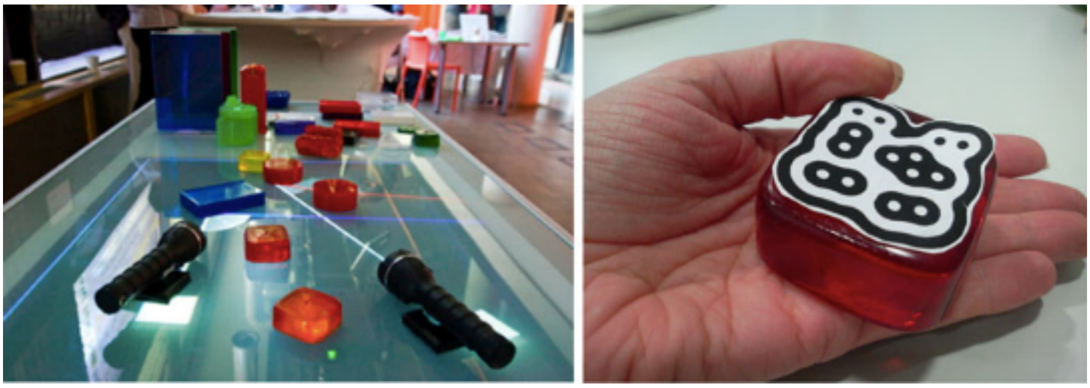


Figure 7.2: The interaction objects and an example fiducial

When distinct objects are recognised by the system, different digital effects are projected onto the tabletop. The torches act as light sources (causing a digital white light beam to be displayed when placed on the surface), and objects reflect, refract and/or absorb the digital light beams, according to their physical properties (shape, material and colour). For instance, as according to the physics of light a block looks green because it reflects the green component of the light spectrum, in this application pointing the torch at a green block causes a green beam to be reflected off the block (Figure 7.3, left). In the case of transparent objects, light is refracted (Figure 7.3, right).

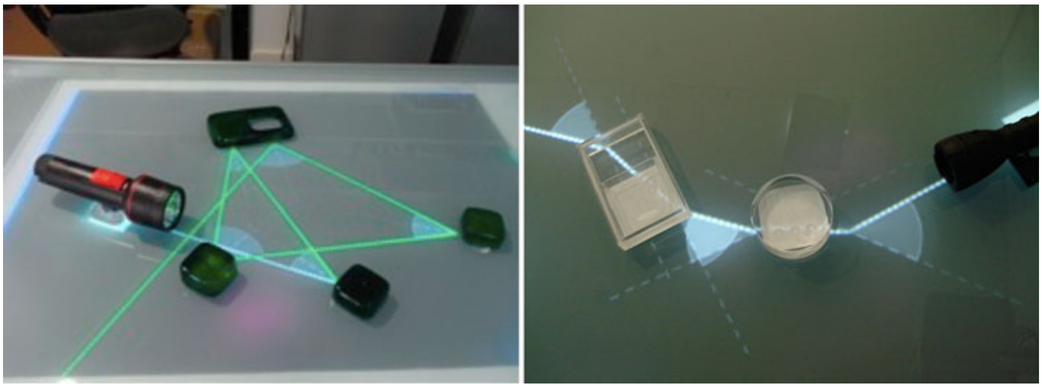


Figure 7.3: Light reflection off green objects (left) and light refraction through transparent objects (right)

The tabletop scenario was designed for small groups of children to explore a tangible simulation together and discover basic facts about the behaviour of light by experimenting with the different combinations of objects. Rather than leading children towards solving well-defined tasks, the application was designed to encourage free collective exploration and promote discovery learning, by making children reason and think about light behaviour.

The tangible tabletop was appropriate to address the research question of how tangible interfaces could support children with intellectual disabilities in a process of discovery learning. Firstly, it was designed to be an exploratory environment, where children were expected to manipulate physical objects in a very intuitive manner and make assumptions about the conceptual domain from such empirical experience. Secondly, the author of this thesis took part in the design of the artefact, and was involved in several empirical studies where typically developing children explored the physics of light with the tangible tabletop. Such studies helped to iteratively model a scenario more suitable for educational purposes (browse the project's publications for more details[4]), and served as an important reference for the studies with children with intellectual disabilities.

The d-touch drum machine

The d-touch drum machine is part of 'audio d-touch', a collection of applications for real-time musical composition and performance (Costanza et al., 2011). The collection to date includes a drum machine and a sampling sequencer, both controlled by spatially arranging physical objects on an interactive surface, which consists of a simple printed piece of paper. The d-touch drum machine is a simplification of musical tables, where objects are placed on an interactive surface to create music (Chapter 4). With d-touch, the spatial arrangement modifies sound, and a surface is repeatedly scanned to identify the location of a physical object and determine the sound to be played. However, no digital effects are projected onto the surface, neither does it react in any visual way. The only feedback given by the system is auditory. Also, the blocks do not communicate with each other - the only identified parameter is their location on the surface.

Object recognition is done through the d-touch marker recognition algorithm, which identifies the objects' labels, also printed on normal paper, via a webcam

[4] http://www.lkl.ac.uk/research/tangibles/publications.html

(Figure 7.4). The objects can be anything, as long as they are tagged with the markers (on top, facing the camera). The information about the position of each block on the interactive surface is used to control a digital audio synthesis process running on a computer.

Figure 7.4: The audio d-touch basic setup – the paper surface, the labelled objects and the mounted webcam
Source: www.d-touch.org

The interactive area of the drum machine is a sheet of paper of size A4, divided in eleven rows, where each one corresponds to a different sound, indicated by text labels. The types of sound produced by the drum machine are: bass drum, snare drum, high tom, mid tom, low tom, rim shot, clap, close hi-hat, open hi-hat, ride cymbal and crash (Figure 7.5). The drum machine is controlled by spatially arranging the physical objects on the interactive area. The vertical position of the objects determines the type of sound that will be triggered, while the horizontal position determines the timing of the sound trigger, within a computer loop. A sound is thus played for each object placed on the surface, repeatedly, within a loop. This allows the user to create percussion-based musical compositions just by placing the objects on the surface.

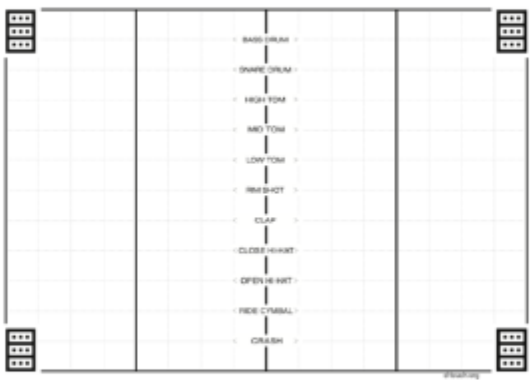


Figure 7.5: The drum machine interactive area
Source: www.d-touch.org

Audio d-touch is an attempt to make tangible interfaces accessible to a larger audience, requiring only products that are easily available (Costanza et al., 2011). The system was designed to be low cost, robust and easy to set up. The software parts of the systems are fully and freely available for download, and detailed instructions are given on the website of d-touch.org, for building the physical interface. Considering that the type of digital representation was a design aspect to be investigated, the availability of d-touch was the main reason for choosing the drum machine as the musical TUI for the present work. Interaction with the drum machine is very simple, consisting of placing and moving objects on a surface to produce percussion sounds, and thus it was hypothesised that participants in this research would be able to interact with it.

The digital manipulatives

Digital manipulatives differ from the tangible tabletop and the d-touch drum machine mainly in the sense that they do not depend on an interactive surface, but are self-contained artefacts with embedded computation. In order to analyse the interaction of children with intellectual disabilities with such kind of self-contained, tangible artefacts and their peculiar characteristics, different from the 'objects-on-surface' setup, two types of digital manipulatives were used in the present research that are described next: the Sifteo cubes and the augmented object.

<u>The Sifteo cubes</u>

The Sifteo cubes are digital manipulatives that have started as the academic project Siftables at MIT. The Siftables (Figure 7.6, left) were compact electronic devices with motion sensing, graphical display and wireless communication that could be physically manipulated to interact with digital information and media. Siftables gave direct physical embodiment to information items and digital media content, allowing people to use their hands and bodies to manipulate these data instead of relying on virtual cursors. According to the authors, Siftables radically simplified the way people interacted with information and media (Merrill, Kalanithi and Maes, 2007). Siftables evolved into the commercially available Sifteo cubes (Figure 7.6, right) that are constantly growing in reach and success. A Sifteo cube is a 1.5-inch block with a clickable, full colour LCD display, a variety of motion sensors and a rechargeable battery. Sifteo cubes connect wirelessly to a nearby computer via a USB radio link. The associated SiftRunner desktop software allows the user to browse and play a variety of games on the cubes. The computer runs the games and plays the sounds. Depending on the games, a number of actions can be performed with the cubes, such as move, shake, flip, rotate and join cubes.

Figure 7.6: The Siftables and their successors, the Sifteo cubes
Source: (Merrill, Kalanithi and Maes, 2007) and sifteo.com, respectively

The Sifteo cubes represent an outstanding evolution since Resnick et al. pioneer work on digital manipulatives, a decade earlier (Resnick et al., 1998). The commercial availability of the Sifteo cubes and the enthusiasm over the potential of such digital manipulatives in the community of tangibles for learning motivated their inclusion in the research. However, more important than that was the flexibility provided by the possibility of running different applications with the same set of cubes. Sifteo is, in fact, a platform for development: the cubes 'become' different things depending on the application that is run. Three applications were chosen for exploring different aspects related to discovery learning: (i) the screen saver, to investigate free exploration; (ii) 'Loop Loop', to analyse further aspects related to interaction with audio representations and compare with the drum machine; and (iii) 'Do the Sift', with a focus on specific physical actions and how this impacts on students' exploration.

The screen saver consists of three squares that move on each cube's screen according to the physical movement performed by the user with the cube. In addition to this, proximity of other cubes makes the squares assume different spatial configurations, as shown in Figure 7.7. The screen saver was chosen as an introductory activity for students to get familiar with the cubes through physical exploration. It is a simple activity that allows children to get to know the basics of interaction with the Sifteo cubes, and at the same time try to infer the rules of the behaviour of the squares on the screen, based on their own experience of manipulating the cubes.

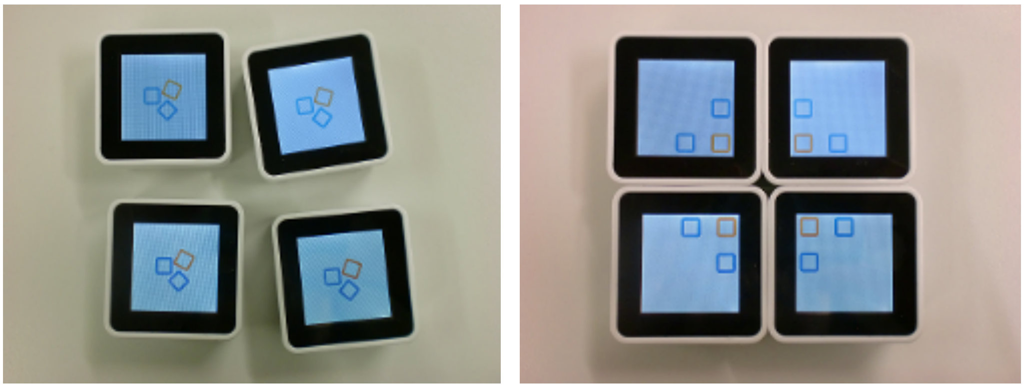


Figure 7.7: The Sifteo cubes' screen saver when cubes are apart (left) and joined in a square (right)

Loop Loop allows the user to create musical compositions by using cubes that have different roles, as illustrated in Figure 7.8. The Instrument Cube contains sixteen different types of sounds grouped into four categories. The user can switch between categories by pressing the cube, and listen to each sound by joining the Preview cube with each side of the Instrument cube. To add sounds and thus compose music, the user must join the Instrument cube with the Mix cube. The Mix cube will play, within a loop, all sounds that were added to each of its sides. Sounds added to the same side are played simultaneously. Sounds can also be removed from the Mix cube by joining it with the Instrument cube, on the side that matches the sound to be removed. Each cube has a different visual representation (graphics, text and colours) indicating its function. For example, the Instrument cube has a colour for each category of sound, and the Mix cube has a dashed line going around the sides to indicate the progress of the loop.

Figure 7.8: Examples of types of cubes in the Loop Loop application

Do the Sift is a simple game that consists of performing actions as 'told' by each cube. At each round, one of the cubes will display an illustration and textual information to indicate which action should be performed with it (shake, flip, tilt, etc.), while the others must not be moved (Figure 7.9). Available time for performing the action decreases as the game progresses, and a wrong action ends the game. Audio effects for game over and correct action, and background music accompany the game. Do the Sift was chosen to explore such variety of actions that could be performed, as well as how children would react to the time pressure and the increasing speed of interaction.

Figure 7.9: Examples of actions of the Do the Sift application

<u>The augmented object</u>

Like the tangible tabletop, the augmented object (Figure 7.10) was developed as part of the project Designing Tangibles for Learning. A polymer cylindrical container was digitally augmented to respond to movement, and to illustrate different phases of motion through which a physical object goes, when a force is applied to it. The object consists of a plastic cylindrical container; Red Green Blue (RGB) Light Emitting Diodes (LEDs); a digital OLED display, a Silicon Labs

C8051F221 micro controller unit (MCU), and an Analog Device ADXL335 3 axis accelerometer sensor. The MCU is responsible for digitising the output of the sensor, calculating the object's speed through integration of the results, and controlling the LEDs' intensity through pulse width modulation. The OLED display is also controlled by the MCU, to enhance the effect of the LEDs.

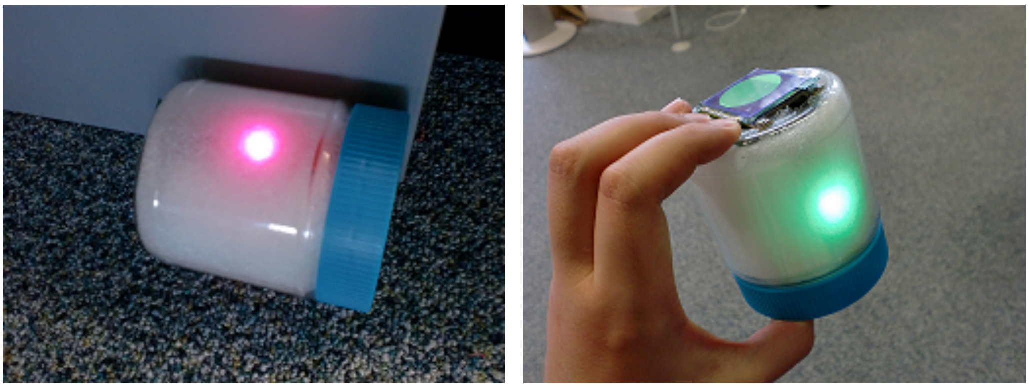


Figure 7.10: The augmented object

Inspired by digital manipulatives like the BitBall (Figure 4.11), the intention of the design was to use this object to dynamically map concepts of speed and motion to different colour illuminations, thus allowing direct experimentation. Colour changes, rather than numerical values, were chosen as augmentation to visually draw attention to changes in the object's motion that would be suitable for children to prompt reflection rather than providing specific answers. The LEDs inside the object and the circle displayed on the external screen change colours according to the movement of the object. Thus, a red LED is illuminated when the object is stationary, green when accelerating and blue when decelerating. However, experimentation showed that in practice, changes in acceleration data occurred in extremely brief periods of time as the object was moved (less than a second), making changes in colour hardly perceivable. On the other hand, as acceleration is determined component-wise along the three axes of motion in the 3D space, changes in direction are also captured by the accelerometer and mapped to the colour scheme. This means that by manipulating the object and rotating it, children can observe the mapping of orientation to colours, which provides an interesting exploration of 'positioning'. Such was the approach used in the empirical studies of the present work. Interaction was thus predominantly exploratory, and the studies design aimed at encouraging a range of unrestricted physical actions, stimulating students' creativity in interacting and interpreting the results.

Design characteristics of tangibles

The four tangible systems described in the previous section covered a range of design features that have direct consequences for interaction, which is of particular relevance to the goal of the present work of analysing how tangibles can support children with intellectual disabilities to productively engage in discovery learning. Such design characteristics are discussed next and presented in Table 7.1.

A first characteristic is the type of digital representation used by the artefacts to provide feedback for the users. Traditionally, visual feedback is the most common type of representation, followed by audio, while haptic feedback is still hard to implement due to technical constraints. The tabletop and the augmented object are uniquely based on visual feedback, while the Sifteo cubes may provide both, depending on the application. The drum machine musical tangible system is uniquely based on audio feedback. The Loop Loop application for the Sifteo cubes was then chosen as a second musical application, but one that also included visual feedback. The influence of such characteristics on children's interaction is discussed in Chapter 8. It was not feasible to include artefacts with haptic feedback in the studies.

Another key characteristic refers to spatial and temporal distances between (i) interaction 'instrument' (or actions performed with it) and digital feedback; and (ii) interaction instrument and interaction 'conceptual object'. The former relates to how close in space and time the manipulation of physical devices and the digital feedback occur (Fishkin, 2004). In the case of the tabletop, physical and digital representations are co-located on the table surface and digital feedback is immediately subsequent to actions. With the drum machine and Sifteo Loop Loop, the audio feedback is separate from the interaction instruments, produced by a computer, and its timing is regulated by a software loop. Visual representations of Sifteo cubes and the augmented object are embedded on the physical objects and synchronised with user actions.

In relation to (ii), in truly direct manipulation, interaction conceptual objects are represented in a physical form and thus serve as their own input device (Beaudouin-Lafon, 2000). The tangible tabletop was designed according to this paradigm: the interaction objects have a role in the simulation that is identical to their role in the physical world, i.e. a green block in the tangible tabletop corresponds to a green block in the physical world. In the drum machine system, there is a distance between the interaction instruments and the conceptual object: the user manipulates a set of objects that are controllers for the abstract object of sound. The physical form of the objects does not hold any metaphorical correspondence (as with the tabletop) to the sounds that are produced. Indeed, the objects are mere tools and have no meaning per se, rather their location has. The Sifteo cubes are somehow in between the tabletop and the drum machine it terms of distance between interaction instrument and conceptual object. With the screen saver application and the Do the Sift game, the interaction and conceptual objects are coincident. For example, when a cube shows the instruction 'shake', the idea is that the cube itself must be shaken: it is not representing anything else. In the case of the screen saver, the cubes also act as objects per se, which have their own behaviour and communicate with others. Loop Loop, for dealing with sound, naturally has a different approach, but which is also distinct from the drum machine. The cubes are controllers, but they are not mere tools. In fact, each one has a meaning, visually represented on the embedded screen, and an associated role in the process of composing music. However, they do not represent the sounds themselves - they can be, at most, containers of sounds. Finally, the augmented object embodies its own representation, so there is no distance between interaction instrument and conceptual object. It is an object to be explored on its own right, however, the behaviour of the embedded lights provides an abstract mapping that relates to positioning, adding a different meaning to the object. As Chapter 8 shows, the distance between interaction instrument and conceptual object was key for intellectually disabled children's comprehension and interpretation of concepts.

Another characteristic to be analysed refers to the possibility of employing multiple objects simultaneously, as it is common in tangible systems. GUIs are based on the concept of time-multiplexing, where a mouse click might evoke different functions and select different objects at different points in time. Tangibles, on the other hand, employ space-multiplexing, where different physical objects represent different functions or data entities, providing persistent mappings. Such persistence enables the designer to take advantage of shape, size, and position of physical devices, as they do not need to be abstract and generic but can be strong-specific, dedicated in form and appearance to a particular function or digital data (Shaer and Hornecker, 2010). The tangible tabletop is based on the physical characteristics of each interaction device, which have persistent individual behaviours. In the drum machine, despite space-multiplexing, the physical devices are abstract, equally and generically shaped, and their appearance does not indicate their meaning or function. In fact meaning is conveyed through the devices' position and not through their shape or appearance. Although the Sifteo cubes are generically shaped, the embedded screen allows for individualisation, i.e. each cube can have a different meaning and represent a different object, taking advantage of the persistent mappings enabled by space-multiplexing. However, the physical appearance of all Sifteo cubes is the same, i.e. they do not exploit other physical properties, such as shape or size to convey meaning. On the other hand, they can engage the user in a variety of physical actions, and 'embody' many different conceptual objects via visual on-screen representations. Finally, although the concept of space-multiplexing does not apply to the augmented object because it is a single device, it is important to say that its shape is also generic and has no specific associated meaning, unlike the tabletop objects. So, meaning making from interaction with the object is rather abstract, and related to positioning, while with the tabletop for example, concepts and representations are more 'concrete', grounded in objects from the physical world.

It follows from this discussion that although tangible systems provide the possibility of indicating meaning and function through objects' appearance, not all tangible systems are designed in that way. This brings to the analysis aspects of metaphorical correspondence (Price and Pontual Falcão, 2009) that play a very important part for children's interpretation and comprehension, besides the role of affordances for allowing (or inviting) actions that have sensible results to improve the mapping of actions to effects (Shaer and Hornecker, 2010). The design characteristics of the tangibles used in the empirical studies are summarised in Table 7.1.

	Type of digital representations	Distance between interaction and conceptual objects	Space-multiplexing
Tabletop	Visual	Truly direct manipulation	Dedicated physical form, persistent mappings
Drum machine	Audio	Interaction devices as controllers of abstract concept	Generic physical form, meaning conveyed through location on surface
Sifteo's screen saver	Visual	Truly direct manipulation	Generic physical form, but allowing for individualisation through screens
Sifteo's Loop Loop	Visual / Audio	Interaction devices as controllers of abstract concept	
Sifteo's Do the Sift	Visual / Audio	Truly direct manipulation	
Augmented object	Visual	Truly direct manipulation	Generic physical form, meaning conveyed through positioning

Table 7.1: Design characteristics of tangibles used in the research

Table 7.1 shows that in the systems that had audio as their main form of representation, interaction devices were of a generic physical form and had the role of controllers of abstract concepts. These two characteristics indicated that these systems could be particularly problematic for the user group. However, including these systems in the empirical studies was useful for reinforcing the inadequacy of such design choices for the population considered, by making a number of problems of interaction and comprehension explicit, as described in the next chapter.

Participants

Similarly to Phase I, the approach of opportunity sampling was adopted for recruiting participants of Phase II, through previous school contacts of the researcher, and by approaching new schools. The important aspect was to select participants who matched the target population of the research, i.e. children with intellectual disabilities. The precise definition of what constitutes an intellectual disability in constantly under debate (Chapter 2). Participants were chosen according to their school's criteria and decision for placing them in a group of children with difficulties to learn, i.e. were selected on the basis of being considered intellectually disabled by their schools, and thus treated as such in their school life, as an heterogeneous group. Such selection criterion is aligned with the socio-constructionist perspective followed by the present work, according to which intellectual disabilities are a socially constructed outcome of the interaction between the characteristics of the child and the environment, derived from culture, values and beliefs. In addition, as discussed in Chapter 2, there is a lack of evidence from the empirical field in favour of syndrome-specific educational interventions, which indicates that an approach that targets the heterogeneous school groups of intellectually disabled students may be more useful.

The context and the target group of the research were explained to teachers, in terms of difficulties presented in Chapter 2, i.e. perception and attention, judgement and reasoning, social communication, and abstraction and generalisation. On this basis, the teachers selected students to take part in the research. In mainstream schools, the students selected typically belonged to bottom sets, were part of a learning needs unit, and/or received some kind of extra support (special classes or the help of a teaching assistant). As justified in Chapter 5, the criteria for selecting the students were the teachers' expertise and opinions, within the context of the research.

Once students were selected, teachers were also asked for a more specific description of each student's profile. The main difficulties that emerged from these reports are presented in Figure 7.11. It is important to note that teachers' descriptions of students varied in detail and specificity, and that one student typically presented more than one difficulty, as shown in the two example profiles below:

> Alicia has a statement of Special Educational Needs and has special support from the Speech and Language Unit. She has expressive and receptive language difficulties. When she is upset or finds trouble with activities, she shuts down and refuses to undertake the school activities ("nothing will make her"). Her home environment is tough and she has a brother who also has difficulties.

Paul has specific learning difficulties that affect his ability to acquire and develop his literacy skills. He has difficulties with concentration, retention skills and communication. Reading is not fluent, concentration is up to 15 minutes. Squint in left eye – wears glasses. Difficulty copying from board. Short-term memory – tends to remember only the last part of instructions. Difficulty telling and repeating information consistently from one day to next. Not confident in class / group discussions.

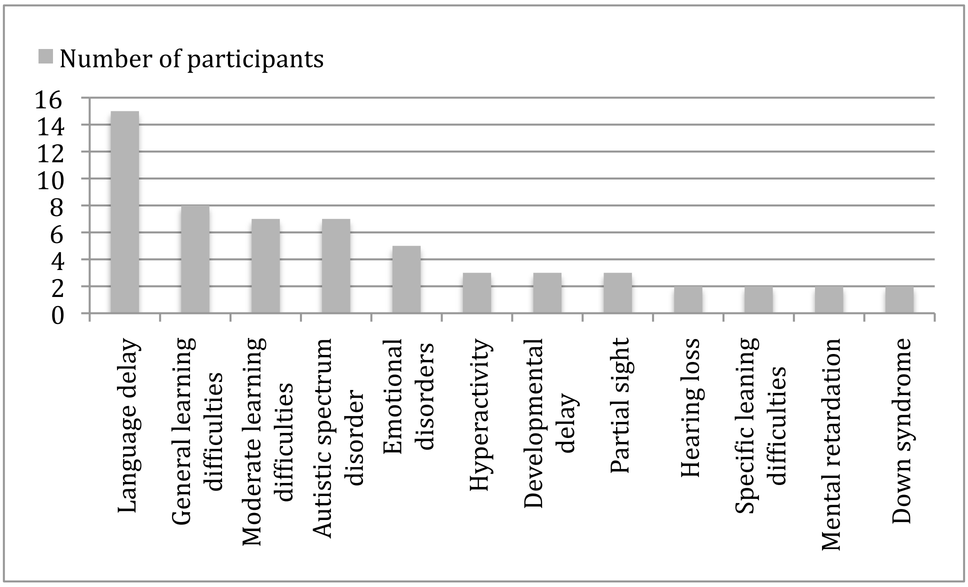


Figure 7.11: Main difficulties of participant students

In particular, partial sight and hearing loss were minor physical impairments that accompanied intellectual disabilities, and not the sole reason for including these children in the studies, as the research does not focus on physical disabilities.

Also according to the teachers' reports of the participant students, the difficulties in Figure 7.11 typically led to lack of self-esteem, high levels of frustration, difficulties with concentration and following instructions.

Based on quantitative results presented in official reports that point to serious disengagement in the transition from primary to secondary school (Chapter 2), the age of the participants ranged mainly from 11 to 13 years. They were in the end of primary or beginning of secondary school. Forty-six children participated in the present research, from five different schools, being three mainstream schools (one primary and two secondary) and two special schools (both secondary). The sample reflected the predominance of males in the intellectually disabled population pointed by gender studies in schools (Chapter

2): there were 31 boys and 15 girls. Schools and participants' names are not revealed for confidentiality reasons. The characteristics of the sample are summarised in Figures 7.12 to 7.14.

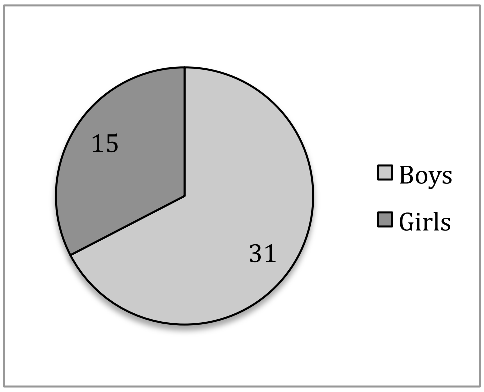


Figure 7.12: Gender of participants

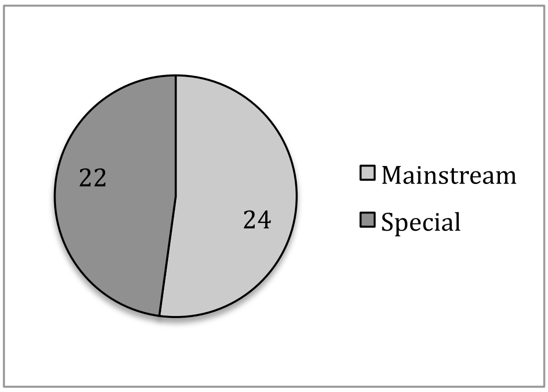


Figure 7.13: Type of school of participants

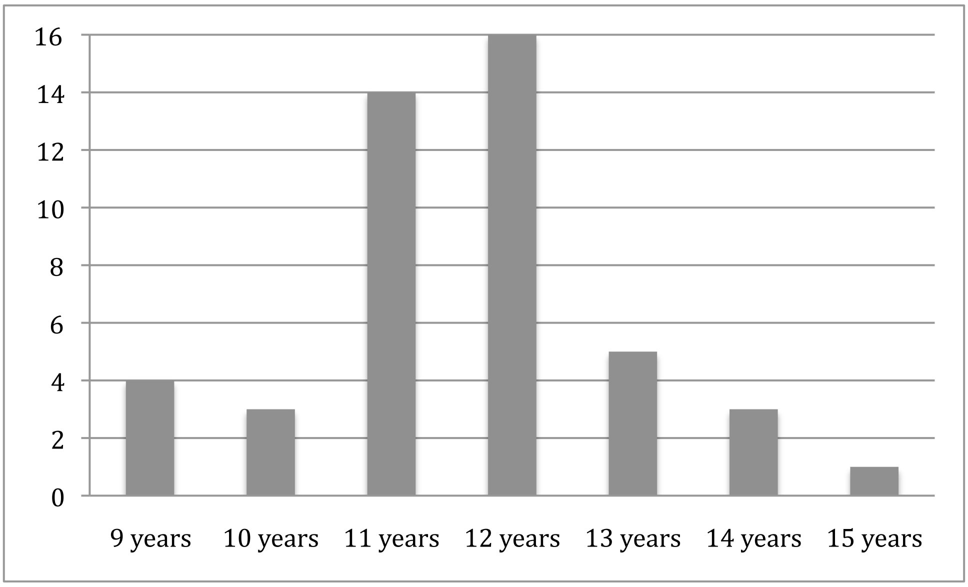


Figure 7.14: Age of participants

Procedure

Besides recruitment, availability and access to tangible artefacts were other complicating factors for running the empirical studies. Similarly to Phase I, the researcher had to be flexible to adapt to the participants' conditions in combination with the limitations of the tangibles. For this reason, the empirical studies were undertaken at different times and in two contexts: at the schools and at the London Knowledge Lab (LKL). As not all tangible artefacts were available at the same moment or could be easily transported, they were not all included in all sessions, as shown in Figure 7.15.

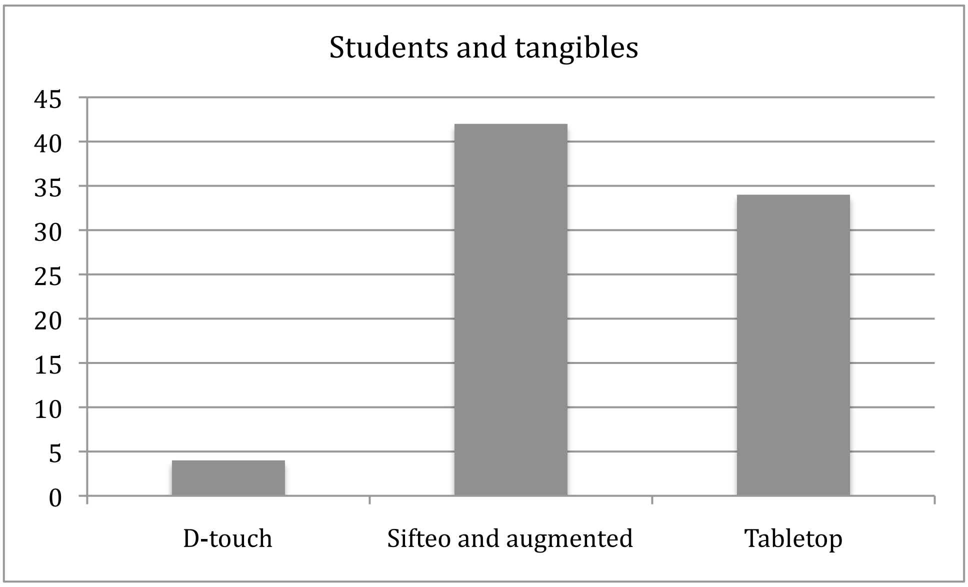


Figure 7.15: Number of students who used each tangible artefact

Overall, studies were designed according to the recommendations elicited in Phase I, i.e.: sessions were kept short; students were informed about the reasons for their involvement in the activities; efforts were made to create a positive environment and make the children at ease; children's pace and capability were assessed and appreciated during each session, leading to adaptations if necessary; and activities were contextualised to relate to students' life. The procedure of each study is explained next.

At the school

Two of the five participant schools were unable to take the students to the LKL, but agreed for the researcher to run the studies at the school. Since the tangible tabletop could not be easily transported, studies in schools included the d-touch drum machine, the augmented object and the Sifteo cubes, according to the availability of each.

<u>Study 1: the d-touch drum machine</u>

The study was run at the resources room of the school. One of the computers of the room was used to run the d-touch software, and the researcher took to the school all other necessary equipment: wooden blocks tagged with markers, an A4 sheet of paper representing the interactive area, a webcam, a desk lamp to serve as a stand for the camera, and computer speakers for playing the sounds

(Figure 7.16). The d-touch software, representation of interactive area, and markers for the objects were all freely downloaded from the d-touch website.

Figure 7.16: The drum machine setup

Four students took part in the d-touch study (2 male and 2 female). They were included in regular classes, but received extra support from a team of specialists of the school, in particular through extra activities in the resources room. The sessions took place during regular school time. Students were told by the SEN teacher that they would play a game with the researcher, and that they should not worry about the activity. All students were willing to participate when invited. The students used the system individually, on a dedicated computer, while normal functioning of the resources room went on as usual. Students worked individually in this study because (i) in this mainstream school, with students included in different classes, the teacher found it hard to make pairs; (ii) the drum machine prototype was rather fragile, and the audio feedback asked for concentration, which made the setup less adequate for pair or group work.

Sessions were facilitated by the researcher and lasted for 6 - 7 minutes, according to the engagement of the child. The aim of the study was to investigate which characteristics of the drum machine could support children with intellectual disabilities to productively engage in discovery learning activities. The procedure adopted consisted of two phases:

1. *Introduction*: the researcher explained that she needed student's help to find out what was positive or negative about the game they would play. Then, the theme 'making music' was introduced. The student was asked which kind of music they liked. This followed the recommendation of

contextualising the activity and relating it to the student's life, while demonstrating interest in knowing about them. The researcher also talked about ways of making music and started producing sounds by clapping hands, knocking on tables, and so on, engaging the student in the activity, which served as an icebreaker to make the child more relaxed and create a positive environment. After this warm-up, the student was told they could use the system to make music.

2. *Exploration:* the student was invited to try the blocks on the interactive surface to see what happened. The researcher let the student explore the system, eventually prompting them with questions like: "what do you think is happening?"; "how can we produce a different sound?"; and "how can we make the music stop?". Such questions were asked in order to assess the kind of conceptual interpretation that the child was making during interaction. The researcher also gave suggestions to the student such as "what if you put a block over here?"; and "do you want to try to take all blocks away to see what happens?", to try and direct the student's attention to some features of the system, and make them understand how to manipulate it. The aim of this phase was to observe the exploratory use that the child made of the system, with minimal guidance. Nevertheless, the researcher intervened when she observed that the child was stuck, or was missing out the functionalities offered by the system. Interventions were made as a way to enrich the child's exploration and the analysis about the characteristics of tangibles. This procedure followed the recommendation of balancing guidance and independent exploration, and encouraging students' own actions and decisions. In addition, as students were simply asked to explore, they did not have a specific task to achieve that could cause anxiety or frustration, and could thus go at their pace and capability. This capability was assessed and appreciated by the researcher during the session.

Sessions were video-recorded for posterior analysis. Findings are presented in Chapter 8.

Study 2: the digital manipulatives

This study was performed in a dedicated resources room of the school. The researcher took all necessary equipment, i.e. the augmented object, the Sifteo cubes, and a laptop computer running the Sifteo software. Eight students took part in this study (5 male and 3 female). The sessions took place during regular school time. Each pair of students was selected by the SEN teacher and was invited in turn to come out of their class to the resources room, while the others carried on with their normal activities in class. All students were willing to participate when invited. Sessions were video-recorded for analysis.

Sessions were facilitated by the researcher and lasted for about 15 minutes, according to children's engagement. Students worked in pairs (i) to make the environment less intimidating and encourage discussion; and (ii) because pair or group work is a common setup in classes, for both practical reasons and pedagogical recommendations (Chapter 6). The aim of the study was to investigate which characteristics of the augmented object and the Sifteo cubes could support children with intellectual disabilities to productively engage in discovery learning activities. The study comprised four activities:

1. *Introduction:* to clarify the situation and the reasons for students' involvement, the researcher gave a general introduction explaining that she needed the students' help in order to find out what was positive or negative about the objects and the games they would play. Each following activity was then better contextualised.
2. *Free exploration of the tangibles:* in this activity, the students were asked to try to find out what was happening to the objects. They were free to explore and talk. In this activity, contextualisation and relationship to their own life were established by the students themselves as they interacted with the objects. The researcher mainly observed, and replied to students when addressed by them. When the students stopped interacting with the tangibles, the researcher prompted them with questions like: "what do you think is happening there?" and "why do you think this is happening?". Such questions were asked in order to assess the kind of conceptual interpretation that the children were making

during interaction. The activity was divided in two parts: first, the students were given the augmented object (turned on). In the second part, they were given the Sifteo cubes running the screen saver. The aim of this activity was to observe the exploratory use that the student made of the systems, with minimal guidance and encouraging students' own actions and decisions as much as possible. As in Study 1, as students were asked to explore, they did not have a specific task to achieve that could cause anxiety or frustration, and could thus go at their pace and capability.

3. *Loop Loop with Sifteo cubes:* after the students had explored the Sifteo cubes with the screen saver, the researcher told them that she was going to 'send a game to the cubes' and started the Loop Loop application. An introduction was given about how one could make music and what kind of music the students liked, as a way to contextualise the activity and show interest in students' life. Students were then told they could make music with the Loop Loop game. The initial idea was to give explanation to half of the pairs about how the system works, and leave the other half to explore it without any explanation, so that students' performance could be compared for these two cases. However, the students had difficulty finding out how to use Loop Loop, and demanded explanations and guidance from the researcher. Since appreciating students' limitations and making concessions, as well as balancing guidance and independence was critical, the researcher altered the procedure to give explanations to all pairs. The specific aim of this activity was to investigate further how students with intellectual disabilities interact with applications based on audio representations, so as to compare with the d-touch drum machine and enrich the findings about such representations.
4. *Do the Sift with Sifteo cubes:* lastly, the students played the game Do the Sift. This was mainly a wind down activity, where students were also left to explore how to play the game. Do the Sift was chosen due to the variety of actions that are performed as part of the game, as well as to

assess the consequences of imposing time pressure and increasing speed of interaction.

Sessions were video-recorded for analysis. Findings are presented in Chapter 8, in conjunction with the laboratory studies presented next.

At the lab

Three schools (two special and one mainstream) took groups of students to the LKL to take part in the main studies. These studies were performed with the interactive tabletop, the augmented object and the Sifteo cubes (d-touch could not be included due to practical issues). The studies took place on three different days, one for each school. Participants in day 1 were 12 students (6 male and 6 female) from a mainstream school, placed in bottom sets, and part of the Learning Development Unit of the school, meaning they had extra classes with the SEN teachers, and extra activities like help with homework, and drill-and-practice with specialised computer programs. Fourteen students (12 male and 2 female) participated in day 2, and 8 students (6 male and 2 female) in day 3, from two different special schools. Students are only accepted to these schools on the basis of being intellectually disabled, and there was a high predominance of boys. Students worked in pairs or groups of three formed by the teachers, according to their total number. Dedicated rooms were set up for the sessions with each tangible system, which were run in parallel due to logistics, time constraints, and to keep the students occupied for as much time as possible during their stay at the lab. The researcher was helped by her supervisor and other colleagues, who were specifically instructed by her to facilitate the sessions according to the planned procedure. All sessions were video recorded for analysis. Each group of students visited each room in turn to interact with each system, being accompanied at all times by a member of staff from the school. Time slots of 30 minutes were allocated for setting up the room and systems for each session, welcoming each pair or group, and running the session. In the lab studies, keeping the sessions short was even more important, as the students went through three different sessions on the same occasion, with short intervals between them. Most students were excited with the school trip and the lab environment, and demonstrated interest in taking part in the activities. There was thus a positive and relaxed environment.

The general aim of the studies was to investigate which characteristics of tangible interaction, provided by the different tangible artefacts, could support children with intellectual disabilities to productively engage in discovery learning activities. In the beginning of each session, the facilitator explained to the students what the activity was about and why they were involved. Students took part in three activities:

1. *The interactive tabletop*: the tabletop was the most robustly designed artefact for exploratory activities, and thus provided a rich environment for discovery learning: different types of objects were available for children to experiment and discover, and the scenarios of the system were designed to encourage reasoning and thinking, leading to assumptions about the conceptual domain from empirical experience. Exploration was encouraged more than over-structured tasks. However, lack of close guidance and tasks, and focus on exploration, as discussed previously, can be serious drawbacks of discovery learning, in particular for children with intellectual disabilities. For this reason, as the tabletop provided space to introduce a more complex procedure than the other artefacts, the level of external guidance given by the facilitator during this activity was varied as follows: (i) low level of guidance in free exploratory sessions, where the facilitator set a general goal or question to be explored and gave eventual guidance on an if-needed basis; (ii) highly structured sessions, where the facilitator guided students through tasks. In exploratory sessions, students were briefly informed how the system worked and what it was about, contextualising the theme within students' life, along with a short practical demonstration by the facilitator, showing the basic functioning of the system and the mode of interaction. Then, the facilitator asked the students to explore the system to try to find out what it was showing. Some prompting was needed when the students were reluctant to explore by themselves, i.e. suggesting to use a specific object and see what happens. Near the end of the session, the facilitator asked the students what they thought was

happening in the system, or to describe what they were doing. In highly structured sessions, the same introductory explanation and demonstration were given. However, after this, the facilitator took the students through the following specific tasks (accompanied by general conceptual questions like "what do you think this is showing?"; "why do you think this is happening?"; and "what do you think this means?"):

1. Can you produce a white beam of light?
2. Can you reflect green light [from the white beam]?
3. What do you think this [the angle of reflection] is? What do you think it's showing?
4. Can you make the green beam point to other directions? What do you have to do to make this happen?
5. Can you reflect red light [from the white beam]?
6. Can you reflect this red light again [from the red beam]? And again?
7. Can you get this [coloured] beam of light absorbed by an object?
8. Can you reflect white light [from the white beam]?
9. Can you get a light beam reflected in many directions? Why is this happening with this object [rough] and not with this other object [smooth]?
10. Can you get the light going through an object? Why does light go through this [transparent] object and not these others [opaque]?
11. Can you get this beam of light through an object making it change colour [use of filter]? Why do you think this is happening?

These tasks related to the main concepts illustrated by the tabletop application about light phenomena. According to the recommendation for appreciating students' limitations and making concessions, terminology of such questions was adjusted to the students' capability. For example, the word 'absorbed' could be replaced by 'stopped'; or 'a green beam of light' can become 'a green line on the table', representing a more concrete way to speak. Not all students were able to grasp the concepts on light behaviour, but it was still possible to analyse their interaction in terms of exploration of the representations provided by the system (e.g. the underlying rules that governed the interaction between the torch and other objects on the surface, and the consequent effects produced), and the role of the system's characteristics in this process. Thus, adapting the terminology was an adequate strategy for this research. After these tasks, students were free to explore the system for a few minutes if they wished, while the facilitator observed.

Comparing the free and guided conditions provided data on the level of external support needed for a productive interaction. It was expected that children would be able to engage with the content even when they were left to a more independent, exploratory interaction, due to the dynamics and interactivity of the system associated with the physicality of interaction devices. It was also possible that the exploratory interaction could give more opportunity for the children to come up with their own conclusions rather than following the facilitator's instructions and answering questions. A less structured environment, i.e. without close guidance from the facilitator regarding what to do, could also make the children feel safer to give their opinions, than when they are expected to solve a specific task. On the other hand, the lack of structure could lead to distraction, or children could not know what to do or what to look for, and therefore not engage with the content. These aspects are discussed in Chapter 9.

2. *The augmented object*: the same procedure for free exploration from Study 2 (at the school) was followed here, where the students were asked to experiment with the object and were free to manipulate it as they wished. The researcher mainly observed, and replied to students when addressed by them. When students stopped or were reluctant to interact with the object, intervention was in the form of questions to stimulate opinions, and suggestions to encourage exploratory actions.

3. *The Sifteo cubes*: the same procedure adopted in Study 2 (at the school) was followed here, i.e. (i) free exploration with the screen saver; (ii) making music with Loop Loop; and (iii) playing with Do the Sift. In the case of Loop Loop, the students were given some time to explore on their

own, although experience from Study 2 indicated the need for explanation. The facilitator was thus prepared for such situation, and provided explanations and demonstrations when noticing students' struggle and disengagement.

Summary

Phase II consisted of the main empirical studies of the thesis, performed with four tangible systems with different characteristics, such as types of representation, forms of giving feedback, mappings between action and effect and repertoire of actions to interact with the artefact. Table 7.2 depicts how the characteristics of the tangibles used cover the design space.

The aim of the studies was to engage children in experimenting with these tangibles, to analyse the contribution of different aspects of tangible interaction for supporting the discovery learning process. To allow such investigation, the empirical studies were designed to be primarily exploratory, which meant that rather than giving right or wrong answers, students were encouraged to explore independently, according to their pace and capability. More task-based, structured sessions were also run with the interactive tabletop with the specific goal of comparing guided interaction with the exploratory sessions, in order to obtain richer and more robust data.

Studies were run on five different occasions and found not only answers but also questions and unexpected aspects, and the object of investigation was refined during data collection and analysis. The exploratory nature and rather broad aim of the empirical studies aimed at discovering more than verifying, aligned with a flexible, evolving and dynamic qualitative research design. The remaining chapters of this thesis present the analysis of the empirical studies and discuss the findings in the light of the literature of the area.

		Modality of feedback		
		Auditory (46)	Visual (46)	Haptic (0)
Spatial coupling	Coincident (42)	-	Sifteo cubes Augmented object (42 used both)	-
	Co-located (34)	-	Tabletop (34)	-
	Separate (46)	Drum machine (4) Sifteo Loop Loop (42)	-	-
Temporal coupling	Immediate (42)	-	Sifteo Screen saver and Do the Sift Augmented object (42 used Sifteo cubes and augmented object) Tabletop (34 out of the 42)	-
	Delayed (46)	Drum machine (4) Sifteo Loop Loop (42)	-	-
Interaction *x* Conceptual objects	Truly direct manipulation (42)	-	Sifteo Screen saver and Do the Sift Augmented object (42 used Sifteo cubes and augmented object) Tabletop (34 out of the 42)	-
	Controllers of abstract concepts (46)	Drum machine (4)	Drum machine (4) Sifteo Loop Loop (42)	-
	Containers of abstract concepts (42)	Sifteo Loop Loop (42)	Sifteo Loop Loop (42)	-
Space multiplexing	Dedicated form / persistence (34)	N/A	Tabletop (34)	-
	Generic form (46)	N/A	Drum machine (4) Sifteo cubes (42)	-

Table 7.2: Coverage of the design space
Numbers in brackets indicate number of students who interacted with each characteristic. Darker cells indicate higher number of students

Chapter 8 – A holistic analysis of child-tangible interaction

Data from the empirical studies were analysed as a single corpus, and not as results from each separate study. This is due to the fact that each study was not designed to investigate different aspects of child-tangible interaction, but they were instances of a same approach to answer the research question. As explained in Chapter 7, studies were performed in different occasions and slightly different conditions due to practical reasons (i.e. number of students, schools' arrangements and availability of tangibles). Tangibles chosen covered a wide range of possibilities for interaction and forms of representations, and the analysis sought to identify themes that cut across the characteristics of the artefacts, focusing on interaction at a higher level instead of being fragmented into each particular system. A second pass of analysis, presented in Chapter 9, focused on the tabletop interaction, based on the results discussed here.

Systematic video analysis was performed through a process of viewing, logging, transcribing and organising the data in the light of the research question, but also remaining open to unexpected phenomena. Transcription and analysis were multimodal, considering talk, gestures, body posture, and manipulation of objects. Although it is generally easier to analyse discourse content, as compared to a sequence of interacting gestures, ideally both should be analysed (Chi, 2009). Human dialogues are normally dense and rich in content (Chi, 2009), but in the case of children with intellectual disabilities, verbal communication can be minimal. According to Vygotsky, the decision process of a child is heavily based on motor skills. A child's movement is full of hesitant, incomplete actions, which reflect the 'motor reasoning' of the child before taking a decision (Vygotsky, 1978). It is possible to identify children's process of investigation of a specific aspect by observing their actions, even though they may not articulate their plans or conclusions. Actions are a form of externalising outputs that is encouraged by tangible systems and formed a primary focus for analysis of children's interaction in the present work.

All video recordings were transcribed, though the level of detail varied according to the relevance of the situation. For example, situations where students engaged in a same action over some time were not transcribed in detail, but rather through a general descriptive sentence summarising what was happening. Excerpts of transcripts are used in this chapter as evidence for the themes analysed. All names were changed to preserve anonymity. As well as textual transcription, passages of video that were especially representative of themes were extracted and grouped into labelled categories in a video editor program, for easy reviewing during analysis, facilitating grouping and classification. Furthermore, still images were captured from the videos and also grouped, to visually illustrate the categories identified.

A systematic examination was performed, marking the transcripts with comments and tags using a traditional text editor program, and associating still images and video passages to the categories generated through identification of patterns. Descriptions of categories were progressively enriched and refined in separate text files, as the analysis evolved. Categories were constantly confronted with existing theories on the object of study, leading to the construction of a coherent and explanatory narrative from data.

The research question that drove the data analysis was: "how can tangible interaction support children with intellectual disabilities to productively engage in discovery learning activities?". The following topics for analysis were used as guidance:

- How do students explore the systems?
- Are students able to engage with the learning content?
- Do students engage with activities unrelated to learning content, and related to:
    - The technology (as in trying to understand how the system works)?
    - Playing with the interface being distracted/ off-task?
- Do students independently/ spontaneously engage in exploratory activities?
    - Do they experiment with different actions?
    - Do they make their own hypotheses and test them?
    - Do they make their own judgements?
    - Are they able to use the system to find answers to open-ended questions?
    - Are they able to draw conclusions from the concrete instances of the

interface?

- Relationships between characteristics of tangibles and students' interaction
    - Types of representations (audio, visual, spatial, textual)
    - Timing of system feedback
    - Types of actions
- Meanings and metaphors involved in the design of the tangibles, and related conceptual comprehension

Although the main focus of the research question was on examining the peculiarities of different characteristics of tangible interaction in terms of how they supported and encouraged exploration and discovery, the topics above show that the analysis was not restricted to this. Furthermore, broad topics enabled discovery and serendipity in the process. This means that the analysis included aspects that were perceived as relevant for child-tangible interaction in the context of intellectual disabilities, not necessarily directly related to exploratory behaviour, but also concerning, among others, interpretation and comprehension, attention and perception, and the role of actions.

As a result of such approach, four general themes emerged from data: types of digital representations; physical affordances; representational mappings; and conceptual metaphors. It is important to note that the four proposed themes are intertwined, and thus one same aspect of child-tangible interaction may be affected by a combination of these themes. Therefore, arguments on child-tangible interaction presented in the remainder of this chapter are progressively constructed as each theme is discussed. For instance, the difficulty faced by children to interact with a musical application was found to be due to a conjunction of factors, like: the perception of auditory representations, the decoupling of input and output, the delayed feedback, and the lack of conceptual metaphors. Each aspect is discussed separately for a better organisation of the analysis, and corresponding illustrative excerpts are presented that focus on each specific aspect. The discussion is progressively incremented and enriched to form a coherent narrative of child-tangible interaction by the end of the chapter.

These themes also contributed to the development of two disjoint sets of guidelines, considering (i) the design of tangibles for children with intellectual disabilities (labelled with 'D' for Design'); and (ii) the facilitation of discovery learning in this context (labelled with 'F' for 'Facilitation').

Types of digital representations

Tangible systems are inherently hybrid. The definition of a tangible interface implies, minimally, a combination of physical and digital representations. Due to the interactional complexity of such type of artefact, representation modalities are discussed here in two distinct categories: digital and physical. This section focuses on the types of *digital* representations provided by the tangible artefacts used in this research, namely: textual, visual and auditory (Table 8.1). Students perceived distinct digital representations differently, and therefore these contributed distinctly for interaction. It is important to clarify that the aim here is not to discuss the connections and relationships that students established between multiple representations (which will be discussed later), but to analyse child-tangible interaction in terms of modalities of digital representations. Although a lot is said in the literature on tangibles for learning, about the benefits and challenges of integrating multiple representations and about the mappings between abstract and concrete that can be facilitated by tangibles, no works were found that focus on the effects of the representations' modalities. The only framework on tangibles for learning that marginally approaches the subject is Price et al. (2008), which includes the modality category, meant to encompass the comprehension of the effects of the different modalities for the learner (Chapter 4). According to the authors, "a key issue is to understand the value of different dynamic representation modalities, and their effects when integrated with each other and with physical interaction" (2008, p. 362). Nevertheless, the authors have not elaborated the modality category in their empirical studies to date. The present research revealed that, when designing tangibles for the intellectually disabled population, modality is an aspect that must not be taken for granted, and is worthy of discussion.

	Textual	Visual	Auditory
Tabletop		X	
Augmented object		X	
Drum machine	X	X	X
Sifteo's Loop Loop	X	X	X
Sifteo's Do the Sift	X	X	X
Sifteo's screen saver		X	

Table 8.1: Digital representations of tangible systems used. Highlights indicate the main type of representation for each system

Textual representations

In the present research *visual* digital representation refers to graphics, pictures, lights/ colours, as opposed to text and numbers. The literature and the field research indicate that hands-on learning is more likely to succeed for children with learning disabilities because of the reduced emphasis on the use of text (Chapters 2 and 6). In this work the use of text was purposefully minimal as no productive results were expected from such type of representation. Indeed, in the empirical studies most children faced difficulties to deal with textual representations. They asked what the text meant or simply ignored the information. Occurrences of text were: sounds' labels in the drum machine's interactive area; action labels of the Sifteo cubes game Do the Sift; and sound labels and a few basic commands of Sifteo's Loop Loop (e.g. 'paused') (Figure 8.1).

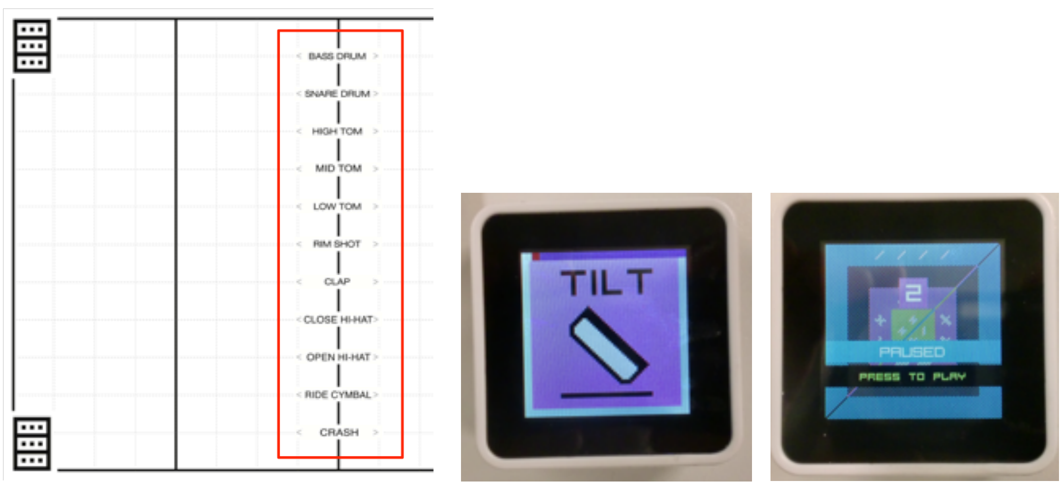


Figure 8.1: Occurrences of text in the tangible systems used: from left to right, the drum machine, Do the Sift and Loop Loop

However, the use of textual representations is not necessarily negative. In fact, it may stimulate children who cannot yet read, to learn it. A good design choice in this case is to always provide an associated pictorial representation to help the child's interpretation of the information. The illustration should be as self-sufficient for interaction as possible, so that the child is not prevented from performing the activity if they cannot read. An example is given in Figure 8.1 (centre), where the instruction 'tilt' is accompanied by an illustration of the action. Another example, a little more complex, is found in Loop Loop's colour differentiation of sounds: for each type of sound, a different colour is used (Figure 8.2).

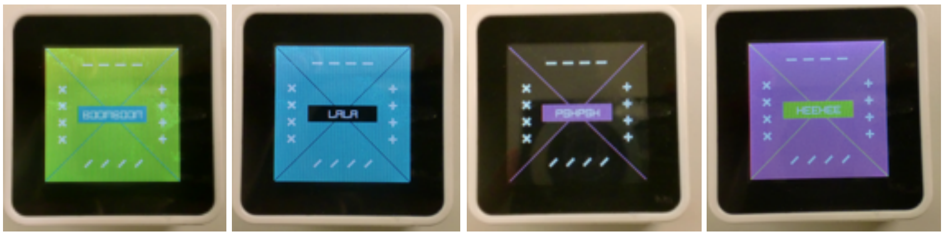


Figure 8.2: Loop Loop's four types of sounds, represented by words and colours (green for 'boomboom', blue for 'lala', black for 'pshpsh' and purple for 'heehee')

Such observations lead to the first derived guideline for designing tangibles for intellectually disabled students:

> Guideline D1: Text should be reduced, and combined with other ways of conveying the same information that do not depend on literacy skills, such as pictorial representations.

Auditory representations

Besides using some text, the Sifteo Do the Sift game made use of a combination of visual and auditory representations. However, sounds were just an accompanying effect to reinforce visual representations, for example, being played for 'game over' and for correct guesses. Such use of sound was generally well received by the students, but primarily had the function of making the game more fun and engaging, and the experience more immersive. This use of sound as secondary to visual representation is common in traditional interface design, where short signals and alerts usually constitute the majority of audio feedback, and sounds are not aimed to represent a specific concept or content (Droumeva, Antle and Wakkary, 2007).

The d-touch drum machine and the Loop Loop application, on the other hand, had audio as their main type of representation, as they are applications designed to make music. The sounds thus form the content, and must be perceived and understood as such, for the interaction to become meaningful. Overall, studies showed that auditory representations were not as easily perceived by the students as visual representations. This is illustrated by the following excerpts of interaction with the drum machine (when a block is placed in the interactive area of the drum machine, a sound is produced - although not always immediately, as explained in Chapter 7).

> Prompted by the researcher, Jacy places the first block in the interactive area. A sound is played.
> ***Researcher: Has anything happened?***
> ***Jacy: No.***
> *Researcher: Can you hear anything different? From the speakers...*
> *Jacy: Yes.*

> Flora followed the instructions to place the blocks in the interactive area, but she showed no reaction to the sounds that were played.
> ***Researcher: Is anything happening?***
> ***Flora: No.***
> *Researcher: What about this noise-*
> *Flora* [interrupting]*: Ah! It's the music!*

Brewster (2002) argues that people's auditory system captures general information from all around, directing their attention to things outside their vision. According to Bly (1982), in certain cases reactions to auditory stimuli are faster than to visual stimuli. Furthermore, while people can choose not to look at something, it is harder to avoid hearing something, which makes sound useful for delivering important information (Brewster, 2002). However, the excerpts above illustrate situations where the students with intellectual disabilities only *perceived* the sounds when they had their attention explicitly directed to the auditory channel by the researcher, despite the fact that they could *hear* the sounds. As discussed in Chapter 2, perception is a fundamental ability for interacting with the environment by dealing with incoming stimuli, and the child must select what is relevant and bring it to the foreground of their attention (Kirk and Gallagher, 1979; Vygotsky and Luria, 1993). As Vygostky argued, intellectually disabled children may have their sensory channels in perfect condition, and still be unable to select relevant stimuli from the environment (Vygotsky and Luria, 1993). Audio may be less easily perceived for being a more abstract and intangible form of representation, and not aligning with the need for the concrete that is typical of children with intellectual disabilities (Chapters 2 and 6). It is acknowledged in the literature that presenting absolute data with sound is difficult and often dependent on subjective interpretation, and that audio information is transient and must be remembered or replayed by the user (Brewster, 2002). The excerpts above show that the students did not initially consider the sounds that played as something that 'happened' as a consequence of placing the blocks, although they noticed the sounds when prompted by the researcher. Relating to Vygotsky's theory above, this means that the sounds produced did not represent relevant stimuli for the students in situations like above, and thus were not brought to attention.

Research has shown that selective attention, auditory blending and auditory discrimination in noise are contributing factors to perceptual deficits (Pressman et al., 1986). Intellectually disabled children were found to perform at a substantially lower level than typically developing groups at tasks that assessed such skills (Pressman et al., 1986). It must be noted that in the present study some of the sounds from the drum machine were quite low, and in some cases the differences between sounds were quite subtle, which made it even harder for students to notice the changes in the music, as illustrated by the excerpt below:

Researcher: what if I want to change the music, make it different?
Flora: different…
Researcher: if I take one of the blocks away, do you think it'll change anything?
Flora: I think so.
Researcher: Let's try?
Flora: Yes.
Flora does not take the initiative, so the researcher starts taking blocks away.
Researcher: has anything changed so far?
Flora: no, it's still the same.
Flora starts taking the blocks away herself. No perceived changes so far.
Flora: it's still the same.
Then there's a sudden change – the music completely stops for a while.
Flora: it stopped!

This excerpt shows that Flora was only capable of noticing an extreme change in the sounds, i.e. from playing to silence. Other changes were too subtle for the student to notice.

Loop Loop provides an interesting comparison with the drum machine. Loop Loop's sounds were very clear and sufficiently loud. However, the accompanying dynamic visual representations on the cubes' screen were too complex for the students. Even when trying to concentrate on the sounds, students were not able to distinguish between different categories of sounds and manipulate them through the visual representations on the cubes, as discussed later in this chapter.

Auditory feedback is an important part of many educational technologies designed for children, and its use is expanding as technologies develop. Going beyond a secondary role to visual representations, sound design is increasingly taking holistic, ambient and ecological approaches, and/or communicating meaningful information such as in the technique of 'sonification' (Droumeva, Antle and Wakkary, 2007). Music-making applications, like d-touch and Loop Loop, are yet another paradigm within sound design that is also increasingly gaining space (Chapter 4).

Analysis here indicates that having sound as a main type of representation and feedback can be challenging for the population of children with intellectual disabilities. However, an important limitation of the present analysis regards the design characteristics of the systems used to investigate audio representations. In the case of d-touch, besides the badly distinguishable audio and the excessively abstract associated visual representations (with no clear conceptual meaning), delayed feedback and non-localised audio interfered negatively in interaction. Although Loop Loop had clearer sounds, it shared similar design features. It became very clear, from the studies, that these are inappropriate choices for children with intellectual disabilities, as discussed later in this chapter. According to Droumeva et al. (2007), the modes of display in children's learning environments need to incorporate the way children use their senses in the natural environment and take into consideration age-dependent perceptual and cognitive abilities. The d-touch drum machine and the Loop Loop application were not good examples of musical applications for this population, and other systems such as the Motion Composer[5] or the Sound Maker (Antle, Droumeva and Corness, 2008) could be interesting alternatives for further investigation of audio representations. Taking such limitations into consideration, findings in this study allow concluding that audio must be very carefully designed, and should not be used as the main type of representation for children with intellectual disabilities when implemented through delayed feedback and distant coupling.

> Guideline D2: Auditory representations must be sufficiently loud, clear and simple, and should not constitute the main or sole form of conveying meaning when action-representation mappings and coupling of representations are not direct.

Visual representations

Visual representations proved to be attractive for the students. The tabletop and the augmented object relied exclusively on visual representations and did not make use of text. In the case of the tabletop, the simple but powerful digital effects (digital light beams) produced when objects were placed on the surface easily and immediately caught students' attention. All groups of children who interacted with the tabletop demonstrated curiosity and interest as soon as they were able to produce visual effects by using the torch on the surface. This was perceived through: children's body positioning very near the tabletop; direction of their gaze towards the interactive surface where the visual effects were displayed; children's expressions of surprise and delight with the visual effects (e.g. "wow!"; "that's cool!"; "wicked!"; "uuhh!"; "done it, done it!"; "the light!"); and their immediate engagement in exploring the system as soon as the visual effects appeared. An example of such engagement is shown in the excerpt and Figure 8.3 below:

> The session starts with the researcher placing the torch on the table, thus producing a digital beam of light. Lawrence, who was standing by the table, **stares at the beam**. The teacher points to the beam.
> *Teacher: oh!*
> Lawrence **immediately reaches for the torch**, picks it up, looks at it, then puts it back on the surface and moves it. Lawrence moves the torch too fast, making the visual effects glitch. He shows signs of impatience as the digital beam goes on and

[5] http://www.motioncomposer.com/

off, and lifts the torch to investigate. The teacher tries to make him move the torch slower or leave it still, by holding his hand.
Teacher: leave it! Stop!
However Lawrence still moves the torch as much as he can, despite the teacher's effort. He rotates the torch, trying to get rid of the teacher's hand and leaning over the table to be able to avoid the teacher's arm and **see the digital effects**. The teacher frees Lawrence's hand, and **he continues moving the torch and observing the visual effects**.

Figure 8.3: Lawrence reaches for the torch (left), tries to free the torch from the teacher (centre), and leans to see digital effects (right)

Similar results were found with the augmented object: visual feedback was immediately and very easily noticed by all students. Evidences include: children's body leaning towards the object; children's gaze staring on the lights displayed by the object and paying close attention to it; children's smiles and verbal expressions of delight (e.g. "looks pretty cool!"; "oh, nice!"; "ooh"); and children immediately reaching for the object and observing the changes of the lights. An illustrative example is shown in the excerpt below and Figure 8.4:

The session starts with the researcher offering the object to the students by saying they can explore and tell her what they think is happening with it. Both students **stare at the object:** Emma **tilts her head to one side** and Bob **leans over the table to level his eyes with the object and see it closer**. Bob takes the object near him to have a closer look, while Emma observes.
Emma [pointing to the object in Bob's hands]*: that's pink and blue, pink and blue*.

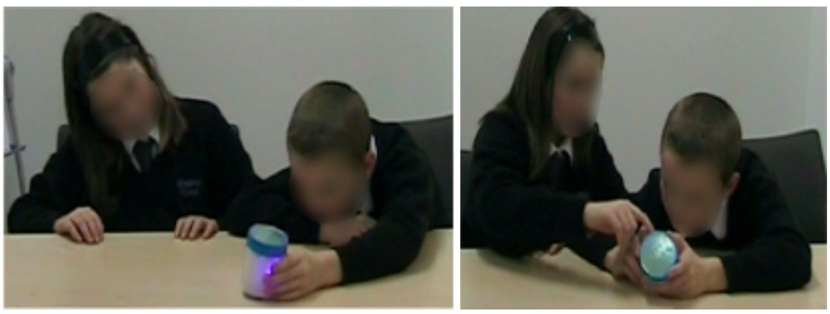


Figure 8.4: Emma observes as Bob leans over and holds the object (left); and Emma points to the object describing the changes in lights (right)

The excerpt shows children's interest in the visual representations, and Emma's comment is a sign of her observation of the changes in representations.

It is important to say that children's engagement here was not solely due to the visual effects. Action-effect coupling and immediate digital feedback importantly contributed for interaction as well, as discussed later. Another important factor relates to the affordances of physical components of the objects, inviting for interaction. However, here the intention is to show that visuals proved to be an adequate and engaging form of representation for children with intellectual disabilities, and stimulated interaction.

Another interesting evidence of the appeal of the visual representations comes from the drum machine. Although this system relies exclusively on audio output, for technical reasons the computer that runs the d-touch software displays on screen the image of the interactive area, captured by the webcam (Figure 8.5). This is not, however, part of the user interface, and is not relevant for interaction - user interaction simply consists of placing the blocks in the interactive area and *listening* to the resulting sounds. Nevertheless, the webcam image on screen naturally caught the students' attention, as illustrated by the excerpts below.

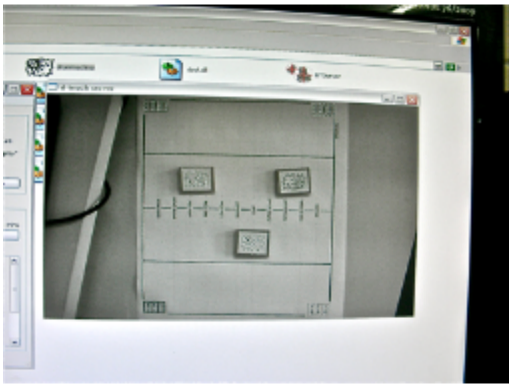


Figure 8.5: D-touch software's image on screen

Researcher: What's happening? As you put these blocks there?
Jacy: I hear… [Jacy **pays attention to the image on the computer screen**.]
Researcher: What is this, that you're looking at there? How do you think this is showing up?
[no answer]
Researcher: Is this similar to something else here?
Jacy points to the interactive area.

The sound produced is too subtle and Joseph does not notice it. The researcher makes Joseph pay attention to the sound, and asks why the sound is being produced. Joseph points to the block in the interactive area, and the researcher suggests putting another one to see what happens. Joseph places another block, but he is more interested in the image on the computer screen than in the sounds. Joseph **notices that every object that he places in the interactive area shows up on the screen, and he gets engaged in observing the changes** in the image.

Jacy also gets engaged with the changes in the image, and in order to investigate them, she places her hand over the interactive area, and checks if it appears on the screen as well (Figure 8.6).

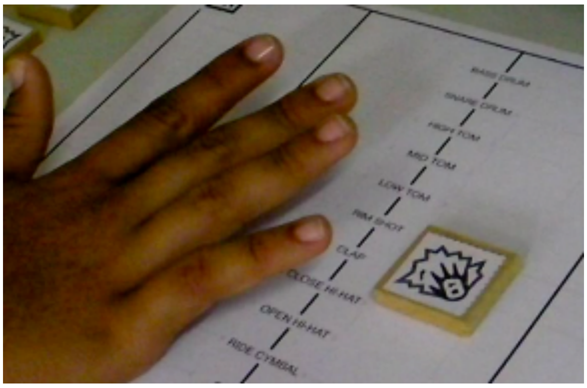


Figure 8.6: Jacy checks if her hand will show on the screen

The excerpts clearly show students going off-task as they engage with the visual representations and ignore the sounds. A similar situation occurred with Loop Loop, although in this case the sounds were louder and more easily noticeable, as mentioned before. Nevertheless, the visual representations on the cubes' screen were still appealing enough to engage students in trying to make sense of them regardless of the sounds produced, missing the point of the application, as illustrated below:

Emma [not paying attention to the sounds produced]*: you get more and more like… these **symbols**, and you get different ones around the **outline**.*
*R: can you **hear** anything happening?*
*Emma: yeah, there's like different **noises**, like…* [holds two cubes together] *the **colours** are getting different.*

In this passage it is easy to see that Emma tends to focus on the visual representations on the cubes' screens (symbols, outline, colours), even when explicitly asked by the researcher about the sounds. Overall, it was observed that, more than listening to the sounds produced, students got interested in the visuals, being it the dynamic symbols of the Sifteo cubes or the screen image mirroring the objects in the interactive area of the drum machine. On the one hand, this reinforces the importance and appeal of visual representations, but on the other, it reinforces how easily distracted children with intellectual disabilities may be by multiple modalities of representations. So, although a straightforward conclusion from the present studies is to recommend the use of visual representations, it must be noted that, if these do not constitute the main type of representation in the system, they have good chances of becoming a source of distraction.

> Guideline D3: For easily attracting attention, visual representations are recommended as a way of engaging students in interaction, but should be discreet if they are not the main type of representation in the system.

This section has shown that, although using multiple forms of representations (audio, video, text, animations, graphics) is cited in the literature as one of the key advantages of digital representations for learning (Clements, 1999; Kaput, 1992; Moyer, Bolyard and Spikell, 2002; Scaife and Rogers, 2005), it brings specific challenges in the context of learning disabilities. Each type of representation must be carefully considered in terms of the abilities and needs of the population. Having examined the effects of different dynamic representation modalities when integrated with each other, as suggested by Price et al. (2008), as far as digital representations are concerned, the discussion moves on to the physical counterparts of tangibles, their affordances and role for interaction.

Physical affordances

Physical affordances are a popular concept in the tangibles literature, as discussed in Chapter 4. The physicality of tangibles is said to provide affordances for actions and multiple users, besides placing constraints on interaction that can guide the user. This section discusses the concept of physical affordances from the perspective of the following sub-themes that emerged from the analysis: confusion from perceived affordances; the importance of spatial configurations of physical components; and the role of actions as imitation, communication and exploration. First of all, however, it is important to clarify the conceptual perspective of affordances taken by this work.

The concept of affordance was introduced into HCI by Norman (1988) drawing from Gibson's theory of ecological perception (1979). Generally speaking, the term affordances is used to denote the possibilities for action that are perceived of an object in a situation (i.e. the functional value of objects and their practical signification) (Béguin and Clot, 2004; Shaer and Hornecker, 2010). In other words, they are properties of an object that invite and allow specific actions (Norman, 1988). Implicitly or explicitly, artefacts prescribe the types of actions that are to be carried out with them, and different representations activate different operations (Zhang, 1997). Affordances can thus be characterised as follows (Béguin and Clot, 2004): (i) the object is significant and this signification is linked to perceptual experience; (ii) the object is immediately - 'automatically' - associated with a signification for action. In spite of the strong link between affordances and perception, Gibson defined affordance as something that does not change with the need of the observer - it is invariant, and always there to be perceived: "an affordance is not bestowed upon an object by a need of an observer and his act of perceiving it: the object offers what it does because it is what it is" (Gibson, 1986, pp. 138-139). Gibson's ecological perspective is contextualised within the relationships between animals and environment, considering biological properties of the world linked to sensorimotor behaviours, e.g. the nutritive and locomotor systems. It never was Gibson's intention to provide appropriate conceptual apparatus for HCI, or in particular for understanding technologies as tools mediating human interaction with the environment (Kaptelinin and Nardi, 2012).

For this reason, Kaptelinin and Nardi (2012) argue for a framework for investigating affordances in HCI based on the interpretivist philosophy and a socio-cultural perspective. Within this theoretical frame, affordances cannot solely depend on the properties of the environment - they also depend on the properties of the *perceiver*, as the environment and the perceiver are mutually constraining and complementary (Zhang, 1997). While Norman simply states that "when affordances are taken advantage of, the user knows what to do just by looking" (1988, p. 9), Quéré prefers the more socio-cultural view that "anyone familiar with the *ways of doing and thinking in a culture, its customs, the objects and mechanisms it uses, its techniques and methods*, immediately and directly perceives the affordances of objects" (1999, pp. 318-319, emphasis added). Kaptelinin and Nardi suggest that a theory of affordances in HCI should be concerned with how affordances are perceived rather than with affordances per se, and that affordances should be understood as "contextualized in unfolding activities and emerging in concrete interaction between the actor and the environment" (2012, p. 969). Hornecker argues that affordances can go unnoticed if they do not fit with real-world experience and cultural knowledge (Hornecker, 2012). Such is the perspective taken here to discuss physical affordances of tangibles: these will not be seen as existing on their own, but rather as emerging from the ways students choose to use the objects. As it will be discussed, in some cases such ways of artefact use were directly derived from the cultural significance of objects, while in other situations they resulted from more complex aspects of interaction.

As discussed in Chapter 3, contrary to traditional pedagogical approaches, bodily activity in tangible interaction for learning is considered to be at the basis of thinking and reflection. Direct physical interaction through body movements, touching, feeling and manipulating are considered crucial (Healy, 1998), as advocated by embodied cognition theories and constructivism. According to Anderson (2003), practical activity plays a role in giving meaning to experiences of, or representations generated by, an individual. Knowledge comes from the actions performed on an object and not from the properties of the object alone (Wheatley, 1991). Providing 'space for action' is advocated by Antle (2007), and refers to bodily engagement with physical objects as a strategy to offload cognitive processes by manipulating the environment. Antle argues that tangibles' inherent spatial characteristic affords opportunities to capitalise on children's repertoire of physical actions. However, Manches and Price (2011) suggest distinguishing between the value of bodily action per se, and the changes in representations that result from taking actions. This relates to two previous frameworks on tangibles: Hornecker and Buur's Tangible Interaction framework (2006), which defines 'spatial interaction' as *moving one's body*, and 'tangible manipulation' as bodily interaction *with physical objects*; and Price's artefact-action-representation framework (2008), where the 'action correspondence' category distinguishes between (body) *movement* and *manipulation* (of physical objects). Tangibles can provide both types of support for children's conceptual development: through bodily action, and through action-resulting changes to external representations.

All tangible systems used in the present research focused on changes in representations resulting from physical manipulation of objects, rather than on the movement of the body as a whole. The focus of the analysis, therefore, is on hands-on rather than on whole-body interaction. Actions were part of the physical engagement of students with the systems, with the feeling of 'doing it yourself', allowing them to make their own choices and think about them. Still, the types of actions that the systems afforded differed, and had distinct characteristics for interaction, in terms of how children manipulated the objects, and reflected about them and about what happened to them.

With the tabletop, meaningful actions were restricted to placing and moving objects on the surface. More than on the meaning of the specific action performed with the body, the focus was on how the system reacted in consequence of the actions performed with the objects. For example, pointing the torch to a green block caused a green beam to be shown on the surface. However, the affordances of the physical objects led students to lift them off the surface and try them in the 3D space, like holding the torch and an object in their hands and pointing the torch to the object. The fact that the objects needed to be on the surface, with the recognition marker facing down, placed important constraints to interaction: children were not free to place the objects on the surface in the position / orientation they wished, as it would be the case were they interacting in the purely physical world.

The physical properties of the augmented object (a cylindrical, light shape) allowed the children to easily move it in their hands, tilt it, shake it, place it still on a surface and roll it on a surface. But beyond these more 'basic' actions, students created metaphors for the augmented object and, within their own narratives, performed actions like pointing the embedded screen to other objects around, pressing or touching screen, and pressing the screen on surrounding objects. Actions were not fixed or predetermined: students were free to choose to do whatever they liked with the object, and they would still get a response from the system in most cases (a change in colour). The focus here was on the movement and position of the object, produced by the different kinds of actions.

Interaction with the drum machine and the Sifteo system consisted of manipulating cubes. As they are sets of identical cubes, children tended to assemble them in different ways. In both systems, there is a fixed orientation for the cubes: screens (in the case of Sifteo) and markers (for the drum machine) must be facing up. With the drum machine, meaningful actions were restricted to placing, removing and dragging objects on the interactive area. Other actions observed included: flipping block, rotating block, and turning block in hand. Actions with the Sifteo cubes that were supported by the system included: joining, dragging, pressing, rotating and others. Additionally, there were actions explicitly prompted by the game Do the Sift: shaking, tilting, flipping, and standing a cube. Other actions observed were moving in hands, piling, and joining screens. Designed affordances and other perceived affordances observed during students' interaction with all systems are summarised in Table 8.2.

	Designed affordances	Other perceived affordances	Technical constraints
Tabletop	• Place/remove object off interactive area • Drag object • Rotate object	• Point torch to objects in the 3D space (off the surface) • Flip objects • Fit squared blocks into larger blocks	• Objects must be on interactive surface • Markers must face down
Augmented object	• Any action in 3D space (tilt, shake, flip, turn, move in hand) • Roll on surface • Place on surface	• Point screen to other objects • Press/ touch screen • Touch screen on other objects	
Drum machine	• Place/remove block from interactive area • Drag block	• Flip block • Rotate block • Turn block in hand	• Blocks must be in interactive area • Markers must face up
Sifteo's Loop Loop	• Drag cube • Join cubes • Press cube • Rotate cube		
Sifteo's Do the Sift	• Drag cube • Join cubes • Press cube • Stand cube • Flip cube • Tilt cube • Shake cube	• Pile cubes • Join screens • Move in hands	• Screens should face up
Sifteo's screen saver	• Drag cube • Join cubes • Press cube • Rotate cube		

Table 8.2: Designed and perceived affordances of tangibles used

In the case of the tabletop, perceived affordances, different from the designed ones (Table 8.2), led to actions that did not produce any digital feedback from the system. The lack of digital feedback, when for example using the torch in the 3D space, made children realise that that action 'did not work', and accept the constraint of the 2D interaction. This 'realisation' proved easier with the tabletop due to the clear link between action and digital feedback provided by the system. With the drum machine, as this link was much weaker (as will be discussed throughout this analysis), children insisted on relying on perceived affordances while struggling to make sense of the system. This showed that designed affordances were not clear, which was a drawback of the interaction. Although a similar situation occurred with the Sifteo cubes, affordances like piling cubes that looked more like toys, even with no digital feedback, remained somewhat meaningful for the children as they evoked activities with traditional assembly kits and allowed them to playfully explore the physical representations. Finally, with the augmented object students were expected to manipulate the object as they wished. Children's emerging metaphors and theories, which had not been anticipated, were interesting indications of how perceived affordances could engender creativity and exploration. Designed and perceived affordances summarised in Table 8.2 are further discussed next in the light of identified themes.

Confusion from perceived affordances

Very often, tangible interfaces are said to take advantage of physical affordances of objects by providing more 'natural' and 'intuitive' interaction (Fitzmaurice, Ishii and Buxton, 1995; Hornecker, 2012; Shaer and Hornecker, 2010). Some of the perceived affordances that emerged from child-tangible interaction analysed here, although perfectly 'natural' and 'intuitive' from a cultural perspective, could be considered counterproductive in terms of conceptual learning - for example, by distracting students from the core concepts that the scenarios were designed to convey. On the other hand, perceived affordances aforementioned revealed students' initiative for exploration, aiming to find out how to deal with familiar objects in a different context, where they did not behave as expected.

Using 'real', meaningful objects like torches and plastic toys, as in the tabletop system, naturally led students to try to use them *as in the (purely) physical world*. This means, for instance, that a torch held in hand can be pointed somewhere (Figure 8.7). Actually, with the tabletop (as with the drum machine), students had to accept the fact that, in this 'new world' objects had to be placed on a specific surface, according to a specific orientation. In addition, technical constraints like the need for having paper markers on all objects of the tabletop system interfered in students' interpretations and led to explanations that were more technical than conceptual, as discussed later in this chapter. Such technical limitations indicate that although tangible interfaces claim to provide natural and intuitive interaction because they resort to physical devices, combining the physical and the digital in a 'natural' way with current technology is still a challenge. This exposes the difficulty of the paradigm of 'Reality-Based Interaction' (RBI) (Jacob et al., 2008), based on naïve physics and on body, environment and social awareness and skills, to match physical affordances and corresponding invited actions with the capabilities of the systems and with users' understanding of interaction (Hornecker and Dünser, 2009).

Figure 8.7: Students try different objects in the 3D space, exploring perceived affordances

Another example of conflict between perceived affordances and rules of the tabletop environment refers to the handcrafted objects of various shapes and sizes. One of these objects was wider with a hole, designed with the specific purpose of illustrating absorption of colours 'inside' objects (Figure 8.8, left). This object was constructed from the same modelling frame as some smaller squared blocks. For this reason, the squared blocks perfectly fitted into the hole of the larger rectangular blocks (Figure 8.8, right). They were made from the same frame for purely practical reasons, but this had an unanticipated effect: many children 'naturally' placed the squared block into the hole of the larger object, expecting something to happen as a result. This coupling of objects, however, not being part of the designed scenario, but a mere consequence of building different objects using a same modelling frame, had no effect at all in the system, bringing confusion to the exploration process.

Nevertheless, students overall were able to explore and learn, at their own pace, the rules of the tabletop system, and reconcile their discoveries with their preconceptions, which constitutes an example of emerging affordances: the objects' affordances stemmed from a dynamic negotiation between intuitions and new rules.

Figure 8.8: The design purpose of showing colours inside object (left), and the squared blocks that perfectly fitted the larger object's hole (right)

A third case of perceived affordances that were not designed comes from the augmented object. This prototype was made out of a plastic container, inside which the electronics were embedded. However, the lid of the plastic container remained visible, and the most straightforward action to be taken by the children was to open it. This was distracting, as children came across the embedded electronics and lost the focus on the designed interactions. In Figure 8.9, the first action of the boys in two different pairs when reaching for the object was to try to open the lid. Jason, on the right, insisted on the action despite the researcher's prohibition, as shown in the excerpt below.

The boys enter the room and researcher makes them sit, and suggests they have a play with the object. Jason grabs the object and starts twisting off the lid.
Researcher: don't take it apart.
Jason **takes the lid off anyway**.
Researcher: put that back.
Jason puts the lid back.
Jason: I can't understand it.

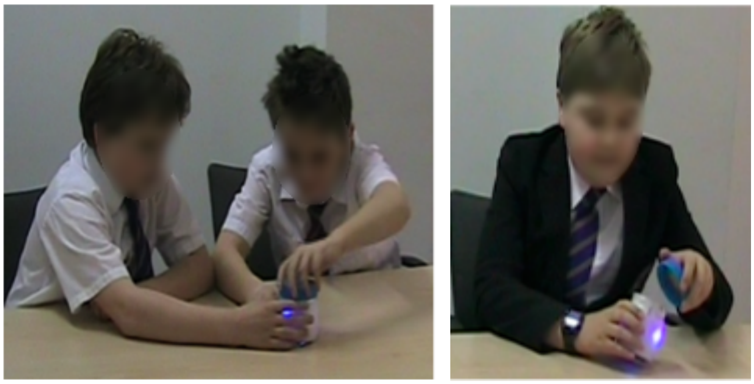


Figure 8.9: Taking lid off as boys' first action with the augmented object

Another example of limitation related to physical affordances refers to the Sifteo cubes. As children were told to press the cubes' screen to start the first activity (screen saver), they immediately took the action of pressing as a - very natural - way of interacting. However, when pressing the cubes again, the screen saver quit. In addition, pressing had the effect of pausing the Loop Loop application. Pressing was thus an action to be avoided more than encouraged, as it did not help exploration. Nevertheless, despite the efforts of the facilitator to avoid the action of pressing, the students engaged in pressing constantly and repeatedly, which caused disruption in the exploratory activity. The excerpts below illustrate such situation:

> [screen saver activity]
> *Researcher: if you want to play with them,* ***you don't press, you move them*** *like this. Look at that!* [changing position of cubes] *Wow, it's changing! Look at this, if you put them together, they change!*
> (...)
> Matt **presses the cubes repeatedly**. The teacher tries to show the boys that **they should not press the cubes**, but move them.
> (...)
> The researcher starts the Loop Loop activity and shows the boys that by putting the cubes together they can make music. At first the boys watch. Then Matt **starts pressing the cubes again**.

> **Suzanne presses the cubes, and the researcher explains that it does not work by pressing**, but by putting them together. Suzanne and Jamal put the three cubes together, but they do not seem to understand how they are producing the sounds. They still press the cubes, **even though they have been told a few times that pressing does not work**.

These findings simultaneously reinforce the value of perceived affordances, and highlight the importance of acknowledging culturally constructed affordances that will not go unnoticed despite the desire of the designer. Physical affordances are indeed so strong in child-tangible interaction, that, for instance, a lid will surely be opened and objects that clearly fit together will be coupled. In addition, inviting actions will be performed even if they do not lead to meaningful results. Physical properties of tangible objects are so inviting that they raise expectations difficult to disregard (Hornecker, 2012), because the human brain processes such properties and basic physical manipulations on a low cognitive level, enabling actions without conscious attention and control (Naumann et al., 2007). In other words, the strength of perceptual cues can bypass conscious understanding and action (Hornecker, 2012). This is also related to what product designers call the 'irresistibles': physical objects' aesthetic interactions, that more than inviting, seduce users (Overbeeke and Wensveen, 2003).

Other studies with tangibles and typically developing children point to similar results on children engaging in actions that were not designed for, nor anticipated, e.g. interacting with: the same interactive tabletop (Price and Pontual Falcão, 2011); the Chromarium blocks (Scaife and Rogers, 2005); and two books using tangibles and augmented reality (AR) (Hornecker and Dünser, 2009). In the case of the latter, the authors report that despite a rather quick comprehension of the general model of interaction with the AR-books, children expected the objects to behave like 'real' objects, attempted 3D interactions the system could not recognize, and kept trying "more of the same" (Hornecker and Dünser, 2009).

This discussion is crucial in discovery learning contexts, where children are supposed to independently explore, and constraints should be implicitly designed. As put by Shaer and Hornecker (2010), in the context of tangibles for learning, physical affordances can place convenient constraints on interaction and manipulation, allowing or inviting actions that have sensible results and thus decreasing the need for learning explicit rules. Nevertheless, if placing constraints to make the user disregard and resist interpretations directly perceived from physical properties may, on the one hand, provoke observation and control of the interaction, engendering reflection, on the other hand it may stop interaction from being intuitive (Hornecker, 2012). It is important to note, however, that the discussion from the studies presented here relates to *disruptive* actions, somehow provoked by physical affordances, and which lead to confusion and/or distraction in interaction. It is not the intention to argue for restraining children's spontaneous engagement in unanticipated actions as part of the exploration process.

The focus on disruption is justified here by the observed peculiarity of learners with intellectual disabilities, whom are harder to prevent from engaging in disruptive or unpredicted actions, as they will not understand explanations nor follow instructions the way typically developing children do, and will thus persist in such actions. This relates to the difficulties (discussed in Chapter 2) presented by children with intellectual disabilities to recall words and phrases and understand their meanings, leading to problems in understanding and remembering instructions; as well as to their tendency for repetitive actions (Cawley and Parmar, 2001; Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000). Thus, while it becomes even more important to design constraints and avoid tempting children with actions that will not contribute to the goal of the activity, or to the exploration process, on the other hand such characteristics of intellectual disabilities also serve to make affordances even more powerful. The difficulty in disengaging children from pressing the Sifteo cubes, for example, reveals the strength of a single instance of learned interaction associated with a natural action, and illustrates how these children easily ignore advice in favour of intuitive actions. This is an important difference from typically developing children, who learn not just from experience but also from instruction, and embrace the latter more readily in case of conflict. For those who are intellectually disabled, testing affordances can be much more critical for engaging in productive discovery learning.

The empirical studies discussed here indicate that affordances that invite actions that *do not have* meaningful results *should not* be apparent / present. Against this, it can be argued that the variability of children's actions found here and elsewhere reinforces the unpredictability of user behaviour and interpretation, associated with the potentially unlimited set of properties and affordances of physical objects, making it very difficult to restrict the set of affordances of a physical interface to those intended by the designer (Hornecker, 2012). As pointed by Hornecker, "relying on affordance in design is far from straightforward" (Hornecker, 2012, p. 2). But, although the guideline stated below does not provide a solution for the unpredictability of users' reactions, and also acknowledging that technical limitations exist, it seems valid to encourage an attempt to go beyond the desired user perceptions of affordances and provide consistent feedback for the greatest range of actions that could potentially be invited by the physical objects in tangible systems. The formulation of this guideline also avoids the temptation of posing excessive restrictions on exploratory interaction aiming to prevent undesired actions, but then contradicting the very purpose of exploration, as alerted by Hornecker and Dünser (2009).

> Guideline D4: Actions invited by physical affordances should lead to useful and consistent effects.

Spatial configurations

Tangibles can represent information through spatial configurations, which is another way of providing support for learners to use external representations (Antle, 2009; Price, Sheridan and Pontual Falcão, 2010). The process of transforming and interpreting configuration of representations is considered crucial for learning, and in particular physical adaptations of the materials encourage the emergence of new interpretations (Martin and Schwartz, 2005). Exploiting human experience of spatiality is one of the particular strengths of tangible interfaces: tangibles can mediate interaction through shape, space and structure (Sharlin et al., 2004). Manipulating spatial arrangements provides a way to support cognition by exploring different relationships, and children naturally explore external representations to construct meaning by restructuring the spatial configuration of the environment (Antle, 2009; Manches and Price, 2011).

Spatial configurations of the physical elements of the systems proved to be a very important aspect for children with intellectual disabilities in the present studies. The tabletop design was heavily based on spatial configurations: the whole activity was about organising the physical objects in different ways to investigate what happened in each case and why. Spatial configuration was thus a central aspect of the interaction. Taking advantage of spatial configurations as the main way of conveying meaning, i.e. the physical organisation of the objects on the surface determining the behaviour of light (illustrated by the digital feedback), led to positive results in terms of students' exploration: interaction flowed easily as students arranged objects on the surface as they wished, obtaining different results according to the organisation of objects. As the interactive surface did not show any indications of how to arrange objects, students had to make use of their own judgement and rely on their own choices, which stimulated independent exploration. As a result, objects were organised on the table by the students in many different ways, as illustrated by Figure 8.10.

Figure 8.10: Students' exploration of spatial configurations: table cluttered with objects (left); a neat arrangement with blue objects (centre); and each child working with a single object (right)

The interactive area of the drum machine (Figure 8.11) has thick vertical lines, and dashed, less perceptible, horizontal and vertical lines, crossing the entire area of the sheet of paper. The main purpose of such lines is to allow the system to identify and determine which sound is to be played, and at which point of the internal computational loop. They can also be used as reference by the person interacting with the system, to help placing the blocks at different positions along the row that corresponds to a certain sound. However, the children with intellectual disabilities were not able to grasp such concepts, and interpreted differently the affordances of the physical blocks and the interactive area. For the students, the lines drawn on the interactive area implied some kind of spatial organisation, and they spontaneously followed some personal rule for placing the blocks, which did not relate to the sounds. They either avoided placing objects on top of the thick vertical lines, tending to place the blocks within the columns, or placed the blocks neatly on top of the lines. At these moments they were clearly concentrating on the spatial organisation and not on the sounds being produced.

Images at the top of Figure 8.11 illustrate Flora's interaction with the drum machine. She neatly placed all available blocks, one after the other, systematically. She started by forming a column of blocks on one side of the central labels, and once completed she repeated the same process for the other side. Flora's organisation of blocks shows she paid close attention to the vertical lines drawn on the piece of paper. The images at the bottom of Figure 8.11 show Jacy's organisation of all available blocks (bottom left), clearly respecting the vertical lines of the interactive area, and Joseph's choice of placing the blocks along the central vertical line (bottom right).

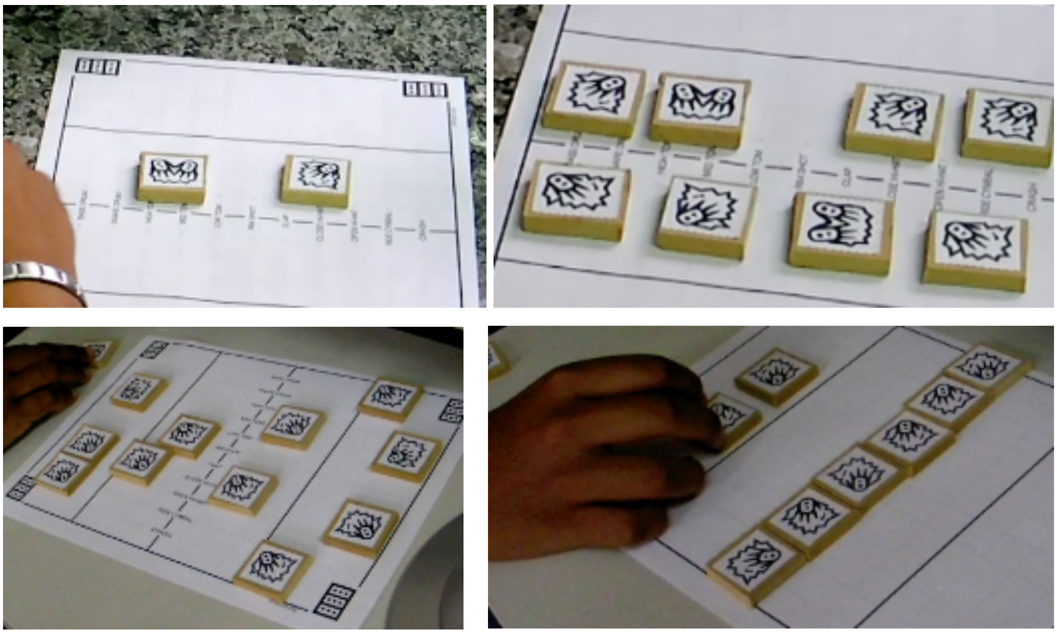


Figure 8.11. The perceived importance of the drum machine's spatial organisation

These findings reinforce the importance of visual representations, now adding the dimension of physical affordances provided by sets of blocks. The combination of the predominance of visual representations over the auditory, discussed earlier in this section, with the physical affordances provided by a set of identical objects and a piece of paper crossed by parallel lines, led children to concentrate on the position of the blocks in relation to the lines, regardless of the sounds being produced.

With the Sifteo cubes, students spontaneously explored a number of spatial configurations like piling the cubes, putting cubes screen-to-screen, joining and putting cubes apart, and building shapes with the cubes. One of the functionalities of the Sifteo cubes is to provide communication between the cubes according to physical proximity, but each application uses this feature in different ways. With Do the Sift, the only feature of the game related to the spatial configuration was lining up all cubes to start each round, while the rest of the game is based on actions with individual cubes. Being heavily based on clear visual instructions, and being a simple instruction-action game, Do the Sift caught students' attention and engaged them in performing actions with each cube at a time. In the screen saver activity, squares on the screens assumed different configurations according to the physical proximity with other cubes. A number of shapes with the physical cubes were possible that led to specific organisations of the digital squares on the screens. The students were able to experiment the spatial configurations to explore the organisation of the squares on the screens (Figure 8.12).

Figure 8.12: Students observe the changes on the screens of the Sifteo cubes

However, students did not limit themselves to the spatial configurations that were designed, also experimenting other arrangements that did not take the digital representations into account. In Loop Loop, cubes should be joined to transfer sounds from one to the other, or to preview sounds. Students built a variety of spatial configurations, oblivious of what was happening on screen and of sounds produced. In these cases, physical affordances were more appealing for the students than digital representations. Examples of spatial configurations unrelated to the digital feedback of the applications are shown in Figure 8.13.

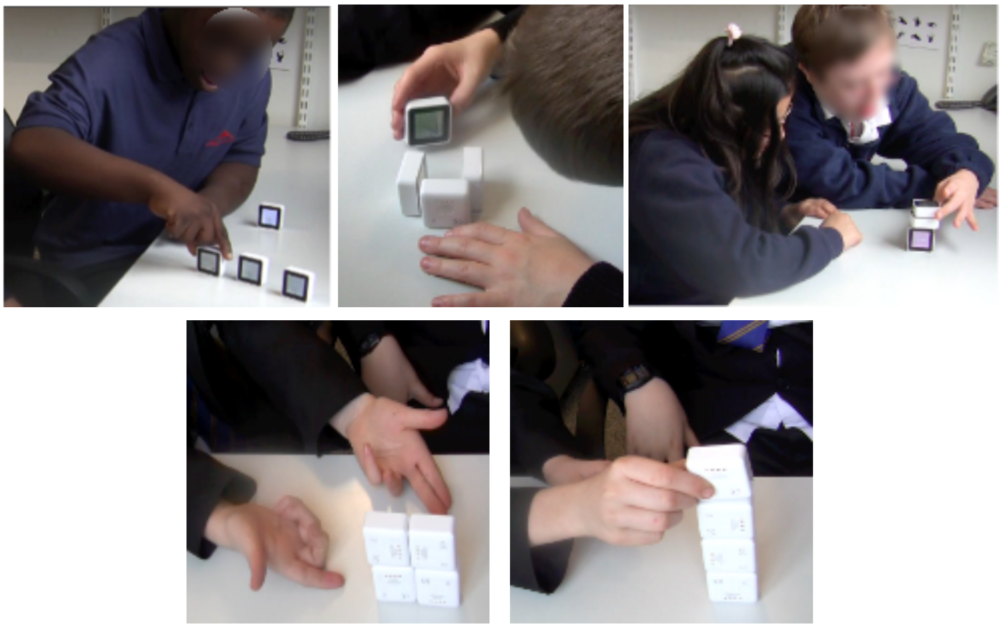


Figure 8.13: Spatial configurations built by students regardless of digital feedback

With Loop Loop, there were also attempts to control sounds through different spatial configurations of the cubes, regardless of visual representations on screen. Students thought they could control sounds by building different spatial configurations with any of the cubes (an example is shown in Figure 8.14).

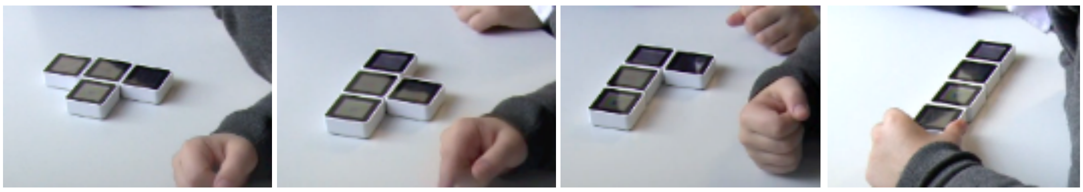


Figure 8.14: Sequence of configurations built by students trying to control Loop Loop sounds

Another example is shown in the sequences illustrated by Figure 8.15, where both Nick and Jamal (in separate sessions) expected sounds to stop or play according to the distance between the cubes.

Figure 8.15: Nick (top) and Jamal (bottom) experiment with cubes apart and together to control the sounds

Realising that the sounds did not stop when he put the cubes apart, Nick decided to increase the distance between the cubes (Figure 8.16). The spatial configuration of the physical cubes was much more important for the students than the specific feature of each cube in Loop Loop and the specific information shown on the screens.

Figure 8.16: Nick takes one of the cubes as far as he can

Observations on spatial configurations revealed important differences between designed physical affordances of the systems used, and the way students interpreted such affordances and used the artefacts. Table 8.3 summarises such differences concerning spatial configurations. The augmented object is not considered here for being a single object.

	Designed affordances	Perceived affordances
Tabletop	Digital effects shown according to spatial configuration of objects on the table	As designed
Drum machine	Position of blocks in interactive area determines which sound is played and when	Lines that compose interactive area served as reference to place blocks within columns or along lines, regardless of sounds produced
Sifteo's screen saver	Configuration of squares on screen depended on specific spatial arrangements of physical cubes	Besides the designed configurations, other spatial arrangements of physical cubes were built, regardless of their lack of effect on the digital representations
Sifteo's Loop Loop	Different cubes must be joined to transfer sounds between them or preview sounds	Spatial configurations of cubes, regardless of their effect on digital representations and sounds, were built. Physical distance between cubes was perceived as a way to control sounds
Sifteo's Do the Sift	Cubes must be lined up to start each round of the game	As designed

Table 8.3: Differences between designed and perceived affordances concerning spatial configurations

Findings confirm the natural expectation that physical objects will, above all, behave like physical objects. So, the challenge of the design is to integrate physical affordances into the hybrid physical-digital context in a meaningful way. In the studies, children spontaneously tried to control the systems based on spatial configurations of the physical elements. The crucial point here is that perceived affordances must be used to bridge the gap between physical and digital representations. This could improve, for instance, students' perception of sound as feedback, given that their natural expectation of controlling sounds through spatial configurations would be fulfilled. When these expectations, based on experience of the physical world, are not met in the system, clear feedback should be provided that counters such expectations. This would help children to learn that some of their intuitive actions (e.g. with building blocks) have different or no meaning in that particular context. For example, it could help them understand that towers of Sifteo cubes will not control the sounds of Loop Loop. However, this is not simple to implement. In a similar context of child-tangible interaction, Hornecker and Dünser (2009) suggest that the system could provide ‘negative feedback’ for actions that do not ‘solve’ a situation, but the authors also acknowledge the risk of desynchronising proprioception, physical world views of objects, and virtual representations of objects, interrupting the flow of the interaction. Such interruption could provoke frustration and discourage exploration. Therefore, there is an important trade-off between informing children of the ineffectiveness of some of their actions and maintaining exploration. In the example of the towers of Sifteo cubes, negative feedback could be in the form of an audio warning, given after repetitive building of towers, indicating that the action is not adequate. Alternatively, feedback could suggest the desired actions by showing a demo on the cubes’ screens. The idea is to drive children away from unproductive actions in a subtle and smooth way, avoiding excessive interference with spontaneous interaction. These observations complement Guideline D4, which argues for the usefulness and consistency of actions invited by physical affordances.

> Guideline D5: Informational feedback should be provided to discourage actions that although invited by physical properties of objects, are ineffective in the system.

The analysis indicates the strength of physical representations for children with intellectual disabilities. As part of their interaction with the artefacts, the students at several moments played with the physical objects as if they were non-augmented, ignoring the associated digital representations, as in the case of Loop Loop, the screen saver and the drum machine. The tendency to experiment several spatial configurations with the cubes, regardless of the digital feedback, may also relate to the children’s familiarity with assembly kits, which in many cases are made of blocks to be arranged in any possible ways. Furthermore, this relates to the preference and need for concrete representations that are common in children with intellectual disabilities and the consequent popularity of traditional manipulatives for this audience (as discussed in Chapter 3). Such appeal was clearly perceived in the children’s interaction with the tabletop. The set of available objects was rich, with different textures, opacities, colours and shapes, which invited children to touch and manipulate them. Thus, also building on previous findings, the strength of each type of representation for children with intellectual disabilities can be ordered as depicted in Figure 8.17.

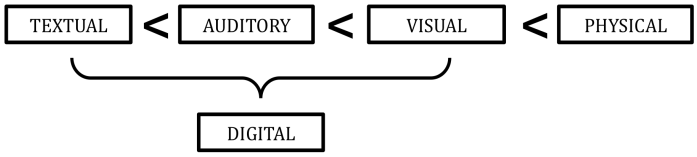


Figure 8.17: Importance of representations in tangible systems for children with intellectual disabilities

Although physical objects are also visual, can produce sounds and carry textual representations, the focus here is on comparing physical representations - treated as inseparable combinations of visual and tactile - with the three types of digital representations designed in the systems to be coupled with these physical 'units', aligned with the definition of tangible interfaces. It is also important to restate the limitations of auditory systems analysed here, which led to the ordering in Figure 8.17, particularly the delayed audio feedback and the distant coupling between physical and audio representations.

The tactile aspect is discussed in this thesis solely within the broader topic of physical representations for two main reasons. First, as mentioned before, haptic feedback to user actions is still hard to implement, and was not provided by any of the tangibles used. Second, the sole case where meaning differed according to tactile properties was the tabletop system, where smooth and rough objects behaved differently. Both the physical components of the drum machine and the Sifteo cubes, within each system, were identical in texture and shape. The augmented object did not embed meaning in haptic characteristics either. Thus, the tactile is rather discussed here as part of physical representations and manipulation.

The predominance of the physical over the digital suggests that, in the context of intellectual disabilities, digital representations in tangible systems must be simple, powerful and attractive, otherwise children tend to focus solely on the physical representations and thus miss the digital feedback. The tabletop system is a good example of effective digital feedback, which was not missed nor ignored by the children. Such discussion, however, will be complemented by an analysis of the physical-digital couplings and the characteristics of the digital feedback that is given by each system, throughout this chapter.

Guideline D6: Design should take into account that children perceive physical representations more easily than digital.

Action as imitation

As discussed in Chapter 2, children with intellectual disabilities are generally reluctant to use their own judgement and take initiative, as a sign of low self-concept and a strategy to avoid failure. As a consequence, they tend to use and heavily rely on external cues picked up from surroundings and on opinions and behaviours of others, as they do not readily recognise features relevant to the task in hand (Kirk and Gallagher, 1979; Scruggs and Mastropieri, 1995). Such characteristics were noted in the empirical studies through students' behaviour in imitating facilitator or peer actions. Examples with the drum machine are shown in the excerpts that follow.

The researcher places a third block in the interactive area. Joseph observes and places a fourth one. **The researcher repeats the action and so does Joseph**.

More than mimicking the action itself of placing a block, students also paid attention to the resulting changes in representation, so as to follow closely what the facilitator had done, as illustrated by the next excerpts, and Figure 8.18:

The researcher places a block in a different area, which produces a louder sound. Jacy says nothing, but also places a block, **on the same column of the researcher's block**.

As the researcher places an object in a different column, **Joseph follows and places another block in the same column as the researcher**.

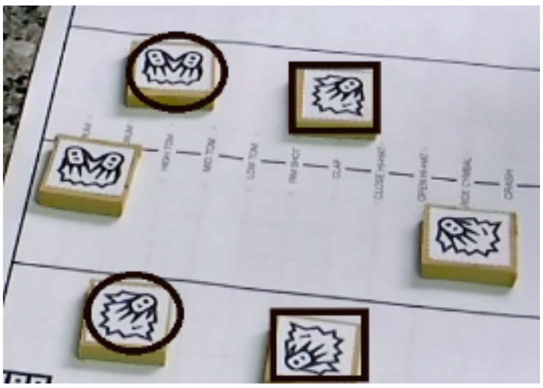


Figure 8.18: Blocks placed by Joseph (marked with circles) after the researcher had placed blocks marked with rectangles

Imitation was also noted with the augmented object. Here the students were free to engage in any kind of action, with no constraints related to screens, markers and camera recognition. There was thus a large repertoire of possible actions, but students often repeated their peer's actions with the objects, as in the example below, where Abel rolls the object immediately after he has seen Dalton do it (Figure 8.19).

Figure 8.19: Abel observes Dalton rolling the augmented object, then imitates the action

Another instance of imitation is illustrated in the excerpt below where two children interact with the tabletop, helped by their teacher. In the tabletop environment, rotating the torch continuously is not a productive action, as it becomes hard to see the digital effects produced. For some reason, however, Jay decided to manipulate the torch in this manner. While Jay interacts with the system, his peer Sue keeps quiet and silent, observing only. When she is prompted by the teacher to interact with the system, she clearly makes a decision of repeating what Jay did.

Jay **makes a complete turn with the torch**, but he does it quickly and cannot see the reflection off the phone box.
Teacher: do it slowly, Jay. Do it again, slowly.
Jay still **rotates the torch** too fast.
(...)
Teacher: All right, let's have Sue. Can you put yours over there, Jay? And let Sue choose something.
Jay removes the torch and phone box from the surface and puts them on the side as told by the teacher.
Teacher: what does Sue want to choose?
Sue shows an orange block to the teacher and she tells her to put it on the surface.
Teacher: have you got your torch, Sue? Where's your torch?
Sue picks up the torch and places it on the table. However, it is not pointing to the object.
Teacher: well done.
Sue starts **rotating the torch, just like Jay did before**. An orange beam shows for a second.
T: did you see what happened there Sue?

Sue tries to stop the torch pointing to the object, but she cannot. Then she **goes on rotating the torch**.

Antle (2007) suggests that it is possible to capitalise on the characteristic of imitation when designing tangible environments. Young children learn through imitation, observing other people using cultural artefacts. According to Rizzo (2006), as children observe others, they attempt to place themselves in the 'intentional space' of others, trying to discern the goal of the other person using the artefact. In this process, they begin to perceive the so-called 'intentional affordances' (Tomasello, 1999) of objects and learn how to handle and use new tools. The theory of intentional affordances draws on the neurology of motor and perceptual pathways to extend Gibson's concept of affordances. It states that not only actions, but also intentions (like to imitate someone else's action) dictate neural pathways (Rizzolatti and Craighero, 2004). Antle's argument is that the physicality of tangibles combined with the space for collaborative interaction and the availability of digital feedback provide the ideal opportunity to design intentional affordances (Antle, 2007). In this sense, three design concepts are suggested by the author: clues to intentional affordances; visual access to performative actions; and turn-taking of physical or spatial controls (Antle, 2007).

Bringing this discussion to the context of children with intellectual disabilities, who tend to imitate others, designing for intentional affordances may be a productive way of indirectly supporting teaching. In particular, relating to Vygotsky's concept of zone of proximal development (Kozulin, 2003), by interacting with the systems together with a more able peer or a teacher, the child with intellectual disabilities, tending to imitate their actions, could be encouraged to reflect about the domain in question. The three design concepts suggested by Antle (2007) were present in the systems used in the studies discussed here. Actions were visible to all participating in the activities, and turn taking of physical objects was prompted when necessary (with sets of objects, children could easily share). Nevertheless, such design concepts were not sufficient for a successful design in terms of intentional affordances. In the case of the drum machine illustrated in Figure 8.18, although the child was imitating the researcher - a more able person - the action of placing a block in a specific region of the interactive area did not help the child reflect. This is partly because the mapping between action and effect in the drum machine is not clear, but also because the decision of where to place a block is the core concept of the application, as it is what determines the sound to be played and how often to do so. The choice of the block's position is thus a consequence of the reflection process, and following someone else's action in this case did not engender reflection, but merely constituted a safe way for the child to interact with the system. On the other hand, with the augmented object, imitation had better effects, as it encouraged more reluctant students to engage in actions they had seen their peers perform, feeling safer to try them. Because the activity was freely exploratory, imitating peers' actions had no negative effects and helped students reflect about the nuances of the object's behaviour as they performed the actions themselves. This also holds for the tabletop system, although the excerpt shown previously reveals important considerations. If, in the situation observed, Jay was a more able peer systematically investigating the environment, Sue could be imitating reasonable / productive actions that could lead her to think about what was happening with the objects that *she* was manipulating. What happened instead was that Sue engaged in the same unproductive action as Jay, taking the same frustrating path, as the children could hardly see the digital feedback.

Such analysis points to a key distinction of the educational context in relation to Tomasello's theory of intentional affordances (1999): the focus here is not on discerning the goal of the other person using the artefact and thus learn how to use it, but rather on providing an environment where, by engaging in the same actions as a peer or teacher, the child will have the chance of perceiving concepts and making conclusions that were not apparent through pure observation of the very same action. So, building on Antle's design principles, Guideline F1 mainly relates to collaborative interaction.

> Guideline F1: To foster learning through intentional affordances and imitation, the intellectually disabled child should preferably work with a more able person.

Action as communication

As discussed in Chapter 2, the expressive domain encompasses vocal and motor skills. Motor skills are not only means of performing physical tasks, they can also communicate feelings and ideas (Vygotsky, 1986). This is particularly important in the case of children with intellectual disabilities, who typically have delays in language development that result in social and communication problems (Kirk and Gallagher, 1979). Tangibles have been used as a support for language and communication for children with special needs, as reported in Chapter 4. LinguaBytes (Hengeveld et al., 2009) and Talking Paper (Garzotto and Bordogna, 2010), for example, are tangible systems aimed at stimulating language and communication skills through physicality and interactivity. Another approach consists of providing additional means of communication other than verbal, as in the case of Enlighten (Cobb et al., 2006), where children can learn how to communicate their choices and needs by shining a torch onto objects.

Using alternative ways of expression and communication was a characteristic that emerged from the child-tangible interaction during the empirical sessions. Overall it was noted that, for the students, acting was much easier that speaking. When asked direct questions, students showed signs of being nervous and fear of giving wrong answers, besides the fact that many of them had difficulties to express their ideas in words, or even to articulate words at all. Actions were thus a way to give answers, explanations and demonstrations to the researcher or peers, without having to verbalise them. For the more able students, who had more developed language skills, nearly all verbal answers to the researcher's questions were accompanied by demonstration with the objects. Indeed, concrete representations are easier to talk about, to describe and to analyse than language-based solutions: it is easier to describe physical actions on physical objects than to describe operations on symbols (Hall, 1998).

The excerpts below illustrate such observations. Firstly, in a session with the drum machine, Matthew says no more than one word, although he interacts with the researcher by performing actions:

Researcher: So there's only one sound playing now. Why is there one only? Look here [pointing to the interactive area]
Matthew **takes the last block away**. All sounds stop.
Researcher: it stopped, didn't it? Why did it stop?
Matthew **picks one block up, puts it briefly in the interactive area and takes it away**.
Researcher: exactly, you took all blocks away. And how can we play that sound again? [Researcher imitates the sound she means]
Matthew **puts the four blocks back**, in the exact same positions as they were before.
Researcher: and how could you make many different sounds? Loads of them?
Matthew **adds more blocks to the interactive area**.
Researcher: so what's happening as you place the blocks there?
Matthew: music.
Researcher: yes, you're making music!

First, Matthew takes a block away to completely stop the sounds. Then, when enquired about why the sounds stopped, Matthew places a block on the surface and immediately removes it, which can be understood as an equivalent to the explanation of 'sounds play when blocks are placed on the surface'. The interaction goes on in this manner, with Matthew replying with actions to each question of the researcher.

The next excerpt, from a tabletop session, shows the difficulty that Donna has when trying to give a verbal explanation about the objects behaviour. Instead of trying to speak, her peer Diane decides to give answers through acting, at the same time showing that she understood the rule.

Researcher: does it go back off the object? You know, in this case, green object on the red light.
Donna: huh... I think it's like... huh... going like back to the object... but it doesn't really... it's not really... there's no green line, so...
Researcher: how can you get a green line with this green object there?
Diane places the green object on the white beam.
Researcher: yes!
Donna moves the green object a bit away from the torch and **Diane places the green cup on the white beam.**

A final example of action as communication is illustrated below, in a session with the augmented object. Jamal is initially monosyllabic, but is able to provide an answer for the teacher by physical demonstration, which ends up leading to a happy celebration that demonstrates the boy's satisfaction with his own performance.

Teacher: did you get green?
Jamal: yes.
Teacher: how did you make it green, did you turn it over?

Jamal: no.
Teacher: how did you make it green, show me again.
Jamal: look…
Jamal starts **shaking the object** energetically, holding it with his two hands.
Then he **places the object on the table, upside down** (green).
Teacher: ah, well done!!
Jamal does high five with the teacher.

Such excerpts reveal that, although most of the time students could not verbally articulate general rules about the behaviour of the tangibles, they showed the rules and concepts they had grasped by performing corresponding actions as a way to answer questions or give explanations. Such use of artefacts and actions as forms of communicating ideas otherwise difficult to articulate also appears in other domains. In participatory design, representational artefacts allow end users with no previous experience in using and modifying design representations to place their hands on the artefacts and simulate work with emerging systems, thus coming up with contributions (Kyng, 1995). Also, advocates of the Programming by Demonstration technique argue that users should be able to instruct the computer by performing actions instead of typing commands of a programming language. The idea is that the computer should be able to create the program that corresponds to the user's actions (Cypher, 1993).

When analysing action as communication in the context of this thesis, it can be said that students were using the artefacts as a way of expressing themselves and their ideas, at the same time as they were exploring them. Important references to discuss expressiveness in the context of tangibles for learning are Marshall et al. work on expressive and exploratory systems (Marshall, Price and Rogers, 2003), and Marshall's framework on Tangibles and learning, which includes exploratory and expressive learning activities as one of its dimensions (Marshall, 2007). However, expressive artefacts, from these authors' point of view, embody the learner's actions to allow them to focus on the external representation of their activity. In an expressive activity, the idea is that learners make their ideas concrete and explicit, and such externalisation then facilitates reflective thought. Therefore, the ultimate objective of an expressive activity is to enable the learner to produce an external representation of some concept, so that they will be able to reflect about it (Marshall, 2007). The analysis presented in this section, however, takes a different focus. Expressiveness in the present work refers to the possibility of communicating through actions performed with a tangible artefact. The role of the artefact, within this specific frame, is to allow students to express their ideas without having to verbalise them. The focus is on *communication* and not on *representations* produced. On the other hand, neither does the present discussion concentrate on addressing communication problems, as the LinguaBytes and Talking Paper systems do (Chapter 4). The idea is to take into account the fact that children with intellectual disabilities have problems with verbal language, and provide alternative ways of communication so that their interaction with the system and with other persons is not hindered due to communication problems. Such alternative ways of communication may not have to be features specifically designed for this purpose, especially because most tangible systems by definition allow the kind of communication through action illustrated in the excerpts presented in this section. In this case, the guideline is more directed to educators than designers.

> Guideline F2: When facilitating interaction, educators should recognise the learners' actions as part of the communication process and favour questions that can be answered through actions.

Action as exploration

Active exploration with concrete materials is a popular approach for students with learning disabilities (Cawley and Parmar, 2001; Mastropieri, Scruggs and Magnusen, 1999; Scruggs et al., 1993). With hands-on activities, students are expected to use their senses to explore and investigate conceptual domains (McCarthy, 2005; QCA, 2001). According to Marshall et al., support for exploratory activities is one of the benefits of tangibles, allowing learners to experiment and observe, while investigating the specific model represented by the artefact (Marshall, Price and Rogers, 2003). In the process of exploration with tangibles, Antle highlights the role of epistemic actions as external scaffolding, i.e. as a strategy to offload cognitive processes by manipulating the environment or objects in it (Antle, 2007). Epistemic actions are performed to uncover concepts or processes that are hard to compute mentally, like visualising, for example (Antle, 2007; Kirsh and Maglio, 1994). Although they do not directly contribute to come nearer the goal of the activity, they help exploring alternatives (Shaer and Hornecker, 2010). Children commonly engage in epistemic actions to facilitate developing new understandings of how things work (Antle, 2007). Tangible systems are said to support epistemic actions for allowing a wide range of actions, including differentiated ones (Shaer and Hornecker, 2010). This section explains how each tangible artefact employed in the empirical studies supported actions as exploration, in terms of: initiation / invitation for exploration; free exploration versus following instructions; and right / wrong answers.

An important barrier for exploration is to take the first step. Antle's *perceptual mappings* refer to perceptual affordances appropriately designed to provide opportunities for action (Antle, 2007). Invitation for exploration is a desirable characteristic of systems that aim to support discovery learning, particularly for children with intellectual disabilities, for whom the fear of making mistakes if higher due to low academic self-concept and predisposition to expect failure (Kirk and Gallagher, 1979; Scruggs and Mastropieri, 1995). In this sense, good results were obtained with the tabletop as it proved to have a very low barrier for initiating exploration. Although most groups of students waited for the researcher to finish the activity's introductory explanation, as soon as they were allowed to interact with the system they started experimenting with the objects. The excerpts below and Figure 8.20 illustrate initiation of interaction with the tabletop:

> As soon as the boys enter the room, Lawrence **comes near** the tabletop and **looks at the objects**.
> *Lawrence* [pointing to the phone box]: *phone box.*
> *Teacher: it is a phone box, well done.*
> Lawrence **reaches for the phone box**, but the teacher stops him, touching him on the shoulder.
> *Teacher: no no no, keep your hands behind, Lawrence. Waiting.*
> Lawrence withdraws. The researcher explains the context to the teacher, while Lawrence keeps looking at the objects, **leaning over the table** to see closer. **As soon as the researcher places the torch on the surface, Lawrence grabs it**.

> As the researcher briefly contextualises the teacher, Paul **stands near the tabletop and leans over the objects** to observe closer. Then the researcher addresses the students:
> *Researcher: So, if you look at these objects, would you say you could use any of them to produce light?*

Paul points to some blocks and Nathan points to the torches.
Researcher [to Nathan]: *yes, so try to put one there*.
Nathan puts one torch on the surface. It produces a beam of light and Paul jumps with surprise.
Paul: wow!
Paul **takes hold of the torch and drags it** on the surface and Nathan **immediately places the other torch** on the surface. The students continue to manipulate the torches, **rotating them**.

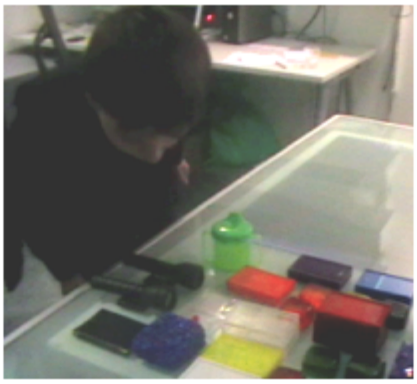


Figure 8.20: Paul leans over the table as he awaits authorisation to start interaction

These excerpts show the students' initial curiosity standing and leaning over the table, followed by immediate engagement with the torches after the researcher's authorisation to start interaction, and by exploration with no further prompts needed at this point. The tabletop also proved to be intuitive: once students started interacting with the system, they needed very few instructions, mostly related to technical constraints (like the fiducial having to face down). Apart from that, interaction consisted of pointing real torches to other physical objects, i.e. it had a strong mapping with situations of the physical world, facilitating exploration. Overall, exploration typically started in a slow rhythm and with few objects, and gradually moved to quicker actions with more objects simultaneously placed on the surface and more complex configurations (as previously shown in Figure 8.10), as familiarity with the technology increased.

The augmented object also presented a low barrier to initiate exploration. Figure 8.21 below shows two situations that illustrate this. On the left, the boy is holding the object together with the researcher, who has not yet finished the introductory explanation. Again, this indicates the child's will to start interacting with the object freely. On the right side of Figure 8.21, the boy grabs the object and starts manipulating it as soon as he enters the room, even before he is seated and before the researcher sets up the activity.

Figure 8.21: Children's eagerness to manipulate the augmented object

Physical exploration continued throughout the sessions with the augmented object, and exploratory actions were particularly creative, due to the affordances of the artefact. The object's shape is generic and there is little structure imposed on the interaction, but the digital feedback makes the object inviting, as shown by the fact that children's attention was directed to the lights as they manipulated the object, as illustrated below and in Figure 8.22:

Abel holds the object in his hands and turns the screen towards himself.
Abel: oh, nice!
Dalton: it's sensing technology.
*Abel: **there's different colours!** Uuu-uuu, do you know anything?* [speaking to the object]
Dalton: give me…
Dalton reaches for the object. Abel turns it in his hands and **looks at the lights on the sides.** He shows it to Dalton.
Abel: oh, nice, look…
*Dalton: yeah, that **changes**.*
*Abel: yeah, that's **green**…* [turning the object in his hands]
Teacher: Abel, let Dalton hold it for a minute.
Abel passes the object to Dalton.
Dalton: about time!
Dalton taps the screen with one finger, and observes **the screen and the lights inside the object**.

Figure 8.22: Dalton manipulates object while observing the lights

Researcher asks students to explore the object (move it, play with it) and see if they find something out about it. Javi picks the object and looks at the screen. He notices it **flickers** as he holds it, and starts **tilting it and observing closely**. The two other boys watch.
*Javier: **changes colour**.*
Javi turns the object in his hands then passes it to Javier.
Teacher: what does it do?
Javi: turn it upside down and it like…
*Javier: **changes colour**.*
Javi [gesturing]*: when it, when it like, feels the movement, it changes colour. The bottom bit, when it feels like movement, it changes colour. When it sees movement.*

The augmented object's loose affordances thus gave the students freedom to explore as they liked, and the actions performed were spontaneous and diverse (Figure 8.23), aiming to find out about the behaviour of the object. On the other hand, as the object is quite limited in terms of the digital feedback it provides (three colours that map to its orientation), it did not sustain children's engagement as much as the tabletop.

Figure 8.23: A variety of actions spontaneously undertaken by the students

The situation was different with the drum machine. Students were reluctant to try it out, as they could not understand the interface, as shown below:

> The researcher chats with Fanny about music. Then, she starts the activity. The piece of paper that represents the interactive area of the drum machine is on the desk in front of Fanny, and the blocks all lie on the side of it. Fanny **does not touch** either.
> *Researcher: So, this system can be used to make music. How do you think we could start, to find out how it works?*
> *Fanny* [smiling]: *I don't know.*
> *Researcher: What can you see on the table?*
> *Fanny: I can see... **oh, I don't know*** [laughs nervously]
> *Researcher: Don't worry, you can say it, there is no right or wrong.*
> *Fanny: I can see many blocks.*
> *Researcher: Yes, and what else?*
> *Fanny: The paper*
> *Researcher: The piece of paper, yes. And what could we do with this?*
> *Fanny: I don't know... Writing, turning the blocks... I don't know.*
> *Researcher: why don't you try something and see what happens?*
> Fanny takes one block in her hand and rotates it, manipulates it a bit. Nothing happens.
> *Researcher: what if you put the block on top of the piece of paper?*
> Fanny **places one block on the piece of paper**.

The excerpt shows that Fanny only performs an action when explicitly guided by the researcher. Before this, the girl shows strong lack of confidence in her speech, being reluctant to give her opinion or to take any action. This situation was noted with all students who interacted with the drum machine, showing that the interface was neither intuitive nor inviting for exploration. Actions were not clear and students were therefore unsure what to do. This is probably due to high level of abstractness of the system, uniquely represented by computational markers and diagrams, and the low intuitiveness of the action of placing blocks on a piece of paper. In addition, no visual digital representations were available to invite exploration.

The activities discussed above did not have specific goals to be achieved or specific tasks to be performed. All undertaken actions were epistemic in the sense of representing ways of exploring alternatives towards a comprehension of the model. It is important to note, however, that the facility to act makes students very engaged in 'doing' but not so much in reflecting upon their actions. In many moments, children were *doing* a lot of things, but without really *making sense* of what was happening. For instance: the Sifteo cubes' affordances, as discussed earlier, were inviting for exploration mainly because they induced actions commonly performed with children's assembly kits. However, children in the studies many times ignored the digital representations on the cubes' screen - which actually conveyed the necessary information for the activity - to concentrate on the physical representations and the actions they could perform with the blocks, as discussed previously. Although children were, in these cases, undertaking rich physical exploration, they were not exploring the system in its totality, and thus not reaching the designed aim of the activity, as interaction was restricted to exploration of a traditional set of blocks. Another example that relates to acting but not necessarily reflecting upon the actions occurred with Loop Loop when students engaged in actions with the cubes to try to control the sounds produced, ignoring the visual on-screen representations. Although this represents an interesting example of action to explore a model, it was not an effective approach to learning how to control the sounds, and students were not able to conclude that their actions did not control the sounds.

These observations relate to the concept of intrinsic feedback (Laurillard, 2012), which is a natural consequence of the action, and serves as a form of guidance for the learner to improve their action, being fundamental to learning through discovery. Intrinsic feedback, by giving the learner more information than right or wrong, should enable reflection on how to change the actions towards productive exploration. The crucial point is that students must be able to make sense of the feedback, and this is where the tangibles described in the situations above failed for these children. Students were not able to work out how to improve their actions from the intrinsic feedback that was designed in the examples cited. This is where the educator must intervene, even within a discovery learning approach. Such intervention would be in the form of extrinsic feedback, which constitutes external evaluation or advice that is not a natural consequence of the action (Laurillard, 2012). Extrinsic feedback is a way of reducing the discrepancies between students' interpretations and the underlying concepts or goals of an activity. It is not easy to design educational technology that always gives appropriate intrinsic feedback, and it becomes even harder when students present variable learning difficulties. Therefore, the presence of the educator is crucial to adjust the provision of adequate feedback.

Guideline F3: For productive discovery learning with tangibles, educators should provide extrinsic feedback when students unable to make sense of the intrinsic feedback produced by the systems.

There were situations where the students themselves sought extrinsic feedback from the facilitator. Still related to the Sifteo cubes, for example, were situations when children did pay attention to the visual representations, but then faced difficulties in understanding the rules of the applications and thus resorted to the researcher's help and explanations. Students worried about what they should be doing and, despite being intrigued by the applications, they were mostly frustrated and disengaged, as they did not understand what was happening, as illustrated by the excerpt below of interaction with Loop Loop.

Bob: do you know what to do?
Emma: No...
Researcher: try to play with them and see what you can do.
Bob [showing cube to researcher]: ***what does it say?***
Emma [holding the Mix cube]: *these parts here, they are moving around. I think like it's on the table and moving.*
Bob: ***I can't do that on mine!!***
Bob presses one of the cubes repeatedly as expecting to get some effect out of it.
Emma giggles.
Researcher: you know how before you had to put them all together…
Children don't pay attention to researcher's comment.
Bob: see if you can move mine then…
Emma: no… [meaning she cannot]
Bob [taking one cube from Emily*]: let me try to move mine...* ***I can't see how this is working****.*

Contrary to the examples discussed before, which illustrated activities where there is no 'doing wrong', here the students were focusing on trying to follow instructions correctly, which decreased physical exploration. Indeed, when extrinsic feedback, like the instructions here, is too detailed, it reduces the learners' own active reflection (Laurillard, 2012). Another situation that also restricts exploration was noted with the game Do the Sift: once the rules were learned, children became very engaged in reproducing the actions as told by the system - however, this does not characterise an example of action as exploration, as it was, instead, action 'as told'. The exploratory approach of the previous contexts, where children did not have specific instructions to follow, involved less pressure and less fear of making mistakes. In addition, actions did not have a 'permanent effect', but rather an exploratory nature. This was perceived by the students, who could do, undo and redo as they liked, knowing that their actions did not mean a definite answer or decision. They could think of how to generate a better action through the intrinsic feedback obtained.

> Guideline D7: To encourage exploration through action, tangibles should capitalise on transient representations (i.e. that can be undone and redone), and avoid right/wrong approaches.

Representational mappings

Typically as children grow, they form increasingly complex associations between concepts and become able to respond effectively to the environment (Kirk and Gallagher, 1979). However a child with intellectual disabilities does not form as complex concept organisations as the typically developing child's (Vygotsky and Luria, 1993), has difficulties in understanding and retaining abstract concepts (Cawley and Parmar, 2001; Holden and Cooke, 2005; Scruggs and Mastropieri, 1995; Stakes and Hornby, 2000), and may never be able to reach conceptual thinking without the scaffolding of concrete representations (Riley, 1989) (Chapter 2). For this reason, as discussed in Chapter 3, manipulative materials are a popular approach for students who are intellectually disabled. Kinaesthetic experience and physical activity are said to enhance perception and thinking, and to help making abstract concepts more accessible by building representational mappings that serve to underpin symbolically mediated activity (O'Malley and Fraser, 2004). Nevertheless, establishing mappings between abstract and concrete representations has been shown to be problematic in learning processes, and the debate on the effectiveness of manipulative materials remains, as it has not be shown to date that these materials adequately support such mappings (Clements, 1999; Goldstone and Son, 2005; Hall, 1998; Kaminski, Sloutsky and Heckler, 2006; McNeil and Jarvin, 2007; Uttal, Scudder and DeLoache, 1997). In other words, it cannot be assumed that children learn abstract concepts simply by touching and moving physical objects (Kamii, Lewis and Kirkland, 2001).

New technologies like tangibles, as mentioned throughout this thesis, bring new possibilities of forms of representation and mappings between them, potentially helping to address students' difficulties in linking the concrete and the abstract so as to form their conceptual understandings (Clements, 1999; Suh and Moyer-Packenham, 2007). However, this potential must be carefully analysed, in particular for children with intellectual disabilities. Tangibles have properties of (i) the physical world where users act upon spaces and artefacts through conventional physical actions and where their understanding is connected to general causal models of the world; and (ii) the virtual world where a mostly unknown set of causal models operate and action is arbitrarily coupled to the properties of the perceived world (Rogers et al., 2002). This context brings into play a number of new interactional and conceptual aspects that must be investigated in terms of their educational benefits. The present section examines two principal factors that emerged from the data and relate to representational mappings and their comprehension: the digital feedback given by the systems in response to children's actions; and the coupling between different representations.

Action-effect mappings

According to Dewey (2001), experience is simultaneously active and passive, i.e. it is experimenting as much as undergoing. There is a vital combination between acting upon something and 'suffering' the consequence, or the intrinsic feedback (Laurillard, 2012), as discussed previously. Thus, for learning to take place, an activity must be consciously connected with its consequences: to 'learn from experience' is to make backward and forward connections between what one does to things and what one receives from things in consequence. In this context, 'doing' becomes experimenting with something to find out about it, and 'undergoing' becomes discovering the connection between things, which leads to learning (Dewey, 2001). When what is received from things as feedback from actions is no longer a matter of chance circumstance, and becomes a consequence of purposive attempts, it acquires rational meaning, enlightening and instructive (Dewey, 2001).

Action-effect mapping is one of the main concepts discussed by the frameworks on tangible interfaces. Aggregating digital effects to physical objects transforms the way individuals experience objects' affordances (Rogers et al., 2002). Hornecker and Burr suggest that tangibles have a great potential for establishing relationships between user actions and effects that are creative and 'magical' while preserving legibility (Hornecker and Buur, 2006). Such legibility of the action-effect mapping is seen by the authors as depending on the 'isomorph effects' through which different representations involved in the system transform the problem. To be easily legible, isomorph effects should preserve the structure of the user's actions by being, for example, close in time or visible nearby (Hornecker and Buur, 2006). This relates to children's principles of cause and effect (Sedlak and Kurtz, 1981), three of which are highlighted by Antle as forming children's 'common sense' of causality: (i) temporal order, which is present in children as young as three years of age, states that causes must either precede or occur simultaneously with their effects; (ii) co-variation states that a causal relation describes an invariable connection between events; (iii) contiguity states that causes and effects must be contiguous in time and place or at least linked to each other by a chain of contiguous events (Antle, 2007).

As mentioned in Chapter 4, Rogers et al. looked at four possible 'transforms' between virtual and physical actions and effects in terms of their level of familiarity for children. The most familiar transform corresponds to a physical action causing a physical effect, and the least familiar corresponds to a digital action causing a physical effect. The authors found that physical interaction and unfamiliarity led to more communication, reflection and exploration (Rogers et al., 2002). Indeed, events that do not correspond to children's principles of cause and effect ideally engender reflection, but may also lead to confusion and/or disinterest (Antle, 2007). These principles can either be supported or broken for educational purposes when designing tangibles for children (Antle, 2007).

This also relates to Price et al. perspective on action-effect mappings as related to causality and intentionality (Price et al., 2008). Causality refers to the system's response to user actions, being 'simple' when this feedback is immediate and conveys a direct association between action/object and effect; and 'complex' when feedback depends on time and/or multiple actions. Intentionality refers to actions that lead to expected effects versus the serendipity of unexpected digital effects (but yet obeying pre-determined technical configurations).

All systems used in the empirical studies provided 'physical to digital' transforms exclusively, which is the traditional interaction mode with tangible interfaces. Nevertheless, there were key differences between systems in temporal and spatial action-effect contiguity, also related to Price's concept of causality, that had important consequences for children's interaction, as discussed next.

System feedback is immediate with the tangible tabletop: as long as the torch is on the surface producing a beam of light, every object placed on the beam's trajectory interferes in some way with the beam, and this is shown as soon as the object is placed or moved. The visual effects on the tabletop system remained the same until students acted on one or more objects. It is therefore an instance of simple causality and direct association between action/object and effect. An example is shown in the excerpt below, from the beginning of a session with the tabletop:

> *Researcher: when you look at these objects here, do you think any of them can produce light?*
> *Boys: yes.*
> *Researcher: which one would you-* [Abel picks one torch] *yes! Try putting it on the surface.*
> Abel **places both torches on the surface, and they produce beams**.
> *Dalton: **oh, that's weird**!*
> Dalton rotates the torches.
> *Researcher: so what do you think this is doing?*
> *Abel: shining. It's like, it's a flashlight.*
> *Researcher: yes, well done.*
> Abel places the phone box on the table. Dalton rotates the torches and points them to the phone box. It reflects red.
> *Researcher: so, if I ask you to produce a green beam of light…*
> Abel puts the phone box back.
> *Researcher: what could you use to produce a green beam of light?*
> Abel **places two green blocks on the surface**.
> *Abel: oh, that's why you have two.*
> Each boy points one torch to one block.
> *Researcher: is it working?*
> *Abel: **yeah! It's working**.*

This excerpt shows that digital effects were very clearly linked to students' actions with the objects, and that, generally speaking, they could perceive this well. Placing a torch on the surface had the immediate effect of producing a beam of light, and placing green objects on this beam produced green light. Abel's opinion that "it's working" shows that students managed to understand the action/object - effect principle of the system, which gave them a feeling of empowerment.

Having said that, there were some factors of the tabletop interaction that influenced perception of action-effect mappings. One is related to a perceived 'lack of feedback'. If an object (except the torch) is placed on the surface but is not in contact with a beam of light, no digital effect is produced (because these objects are not sources of light). In addition, for most objects, the phenomenon of absorption is represented by the interruption of the beam of light, i.e. no extra effect is produced to illustrate it (the exception being the few objects designed with a hole, a tentative representation of the spectrum of colours inside the object). Both are design choices based on the conceptual domain and within technical constraints. Again, this relates to the challenge of designing intrinsic feedback that becomes meaningful for the learners. The design choices for the representation of absorption did not work well for the students, who interpreted them as "nothing is happening" / "it's not working" / "it doesn't do anything", as shown in the excerpts below:

> *Researcher: so what do you think would happen if you took a block in another colour and put it there?*
> *Darren: I don't know.*
> *Researcher: you can try!*
> Darren replaces one of the red objects for a yellow block, and **it stops the red beam**.
> *Researcher: so what's happening?*
> *Darren:* ***it hasn't done anything****.*

> Researcher offers torch to girls and asks them to put it on the surface. Charlotte picks the torch but hesitates as to how to place it. Researcher helps with instructions. Charlotte rotates the torch, then Fatima rotates the torch. Charlotte places the black wallet on the surface, and tries rotating it, regardless of the torch or of the beam of light. She moves the wallet a little, as Fatima moves the torch. At one point **the beam is blocked by the wallet**, **but the girls do not react to it and Charlotte puts the wallet away.**

The excerpts indicate that the phenomenon of absorption was not perceived due to lack of informational feedback. Absorption, for the students, merely corresponded to a 'lack of effect', which did not make them reflect about what was happening (which is the goal of intrinsic feedback by definition (Laurillard, 2012)), but rather ignore it, as illustrated by explicit utterances of "nothing is happening" or actions like Charlotte simply putting the wallet away (excerpt above). The reactions to the visual representation of absorption shown in these excerpts were found for all groups that interacted with the tabletop. This indicates that, for children with intellectual disabilities, feedback must be provided through explicit representations, and not by embedding meaning in the absence of effects.

> Guideline D8: Digital feedback should preferably be represented through production of effects, rather than absence of effects or interruption of current events.

Another factor that relates to action-effect mapping is interference. Based on previous work, interference here is defined as "interruption, change in the flow, or conflict, provoked by the learners during collaborative interaction in the environment" (Pontual Falcão and Price, 2011, p. 9). In other words, it happens when one student takes some action that has consequences for the current arrangement of objects on the table, and for the interaction of the other peer. Although interference is not necessarily negative and may engender reflection (Pontual Falcão and Price, 2011), in the context of action-effect mapping it means that a student may not understand the cause of certain effects, or may associate them erroneously with some action, as shown in the excerpt below:

> Emma chooses three objects: the rough red object, an orange rectangle block, and a red square block.
> *Emma: that go there, that go there…*
> While Emma carefully places her objects in line, Bob is also adding objects to the surface. As he does that, he creates digital effects that **spread over the table, including the area where Emma is working.**
> *Emma: **what the!! How have you done that? Oh, that's mine…***

Emma was focused on her arrangement and then was disturbed by what Bob was doing, and did not understand what was happening. Previous work with typically developing children has demonstrated how interference in the tabletop scenario may be productive, neutral or counterproductive (Pontual Falcão and Price, 2011). In the present studies, children with intellectual disabilities tended to collaborate less and focus on their own individual activity. Even when explicitly prompted to do so, these students showed great difficulties in working together. For this reason, overall, interference did not lead to productive situations of joint reflection and collaboration, but rather to attempts to mitigate peers' actions, as shown below:

The three boys are very active at this point, but uncoordinated, and interfere a lot on what the others are doing.
Jake: if you make that white beam [placing the white object on the torch's beam], *that white beam, yeah? That red one can go…*
Jake hesitates as to where to place the objects, as he's not sure what he's trying to do.
Jake: that blue one can go on that beam… we need another white one.
Jason places a green block but Jake removes it.
***Jake: no no, don't put that green down*.**
There are no other white objects. Jake picks a transparent object as if it was white, and places it on the white beam.
Jake: another white one [**placing the transparent block**].
Jason removes the transparent block.

It is clear from the excerpt above that Jake is pursuing individual goals as he explores the system, while he systematically rejects Jason's interference, which is solely perceived as diverting him from his objectives. Investigating collaborative exploration in detail is out of the scope of this thesis, but interference in the context of action-effect mappings is further analysed in Chapter 9, in terms of how it contributed or hindered exploratory activity.

A third aspect that interfered with action-effect mappings in the tabletop system was technical, and related to glitches and delays of the digital effects in relation to the physical movement performed with the objects, for example when students moved the torch too fast as shown below:

Jay moves the torch very little, rotating it slightly.
Teacher: move it round…
Jay obeys, but he rotates the torch to the opposite side of the phone box.
Teacher: moving, moving...
Jay makes a complete turn with the torch, but he **does it quickly and cannot see the reflection off the phone box**.
Teacher: do it slowly, Jay. Do it again, slowly.
Jay **still turns the torch too fast**. The delay and lags of the digital effects are very clear, as the beam does not follow exactly the movement of the torch.
Teacher: very slowly… watch! [A red beam shows up for a second, from the phone box].
Jay stops and leaves the torch pointing towards the object, but the beam still doesn't touch it. (...) Seeing that Jay doesn't point the torch to the object, the teacher goes next to him, takes his hand, and points the torch to the object, with him.
Teacher: very slowly… oh! What's happened, Jay?
A red beam is reflected off the object.
Teacher: ***what's happened?***
Jay: ***a red*.**

This excerpt illustrates that Jay can establish the link between action and effect, as soon as he can perceive the digital feedback. However, it was quite a long process to get to such feedback, as Jay could not regulate his mode of interaction according to the technical constraints of the system. Other technical restrictions that interfered with children's interpretation of action-effect mappings included: placing objects near the edges of the table (because they were not detected by the camera); keeping the fiducials facing down; and keeping objects on the surface. Usually, the researcher guided the students through recovery from such situations. This points to the importance - particularly in the case of children with intellectual disabilities - of building systems where technical aspects are transparent for the users, and running user tests to determine to best calibration between interaction devices and digital feedback.

The augmented object constituted another example of immediate feedback and temporal contiguity: movements performed with the object made lights change colour. It is also another instance of simple causality and direct association between action and effect. Action-effect links were easily established, as illustrated below:

> Researcher asks boys to explore the object and see if they find something out about it. Javi picks the object and looks at the screen. He notices it flickers as he holds it, and starts tilting it and observing closely. The other two boys watch.
> *Javier: changes colour.*
> Javi turns the object in his hands then passes it to Javier.
> *Teacher: what does it do?*
> *Javi: **turn it upside down and it like…***
> *Javier: **changes colour**.*
> *Javi* [gesturing]: *when it, **when it like, feels the movement, it changes colour**. The bottom bit, when it feels like movement, it changes colour. When it sees movement.*

Although most children easily identified the link between their actions and the digital feedback provided by the object, several different theories came up to try and explain which other factors could be contributing to the object's behaviour as discussed before, such as picking up colours from the environment. Still, after some initial interaction, students proved to have understood the rules involved in the action-feedback relationship as they could obtain specific colours when explicitly asked to.

In terms of action-effect mappings, the drum machine differed from the tabletop and the augmented object in temporal contiguity: feedback could be delayed, meaning that causality was complex. This had a crucial negative effect for students' interaction with the system. After the student had placed a block in the interactive area, the timing of audio feedback of the drum machine depended on the loop within which the system sequentially read each row of the interactive area. The duration of this time lag varied and could not be explicitly adjusted by the user. In practice, this meant that sounds were not necessarily played the moment a block was placed on the surface, and did not necessarily stop the moment the block was withdrawn. This made it very hard for students to associate sounds to their actions with the tangibles and build a link between action and effect. The two excerpts below show situations that clearly illustrate the importance of temporal contiguity:

> Matthew puts a block on the surface. After a short time a low sound is played, but Matthew doesn't notice. The researcher suggests that he brings the speakers closer to his ears. Matthew hears the sound as it plays again.
> *Researcher:* ***do you think it has anything to do with what you did here?*** **[no answer]** *Try putting another block.*
> Matthew places another block. No sound is played the moment he does it.
> *Researcher: has anything changed?*
> Matthew **shakes his head**.
> *Researcher: do you want to explore a bit more?*

> Fanny places one block on the paper. A sound is produced immediately.
> *Researcher: Has anything happened?*
> *Fanny: Yes*
> *Researcher: what happened?*
> *Fanny:* ***it's making a sound***
> *Researcher: exactly!* ***How has this happened?***
> *Fanny:* ***because I put a block.***

In the first passage, feedback is delayed, and Matthew is not able to establish a link between what he is doing with the blocks and the sounds that are produced. In contrast, in the second passage, feedback happened to be immediate, and this allowed Fanny to give a causal explanation for how the sound was produced due to her actions. However, even after having understood that the blocks caused sounds to be played, delayed feedback was one of the aspects that made it hard for students to be able to control the sounds.

A similar situation occurred with Sifteo Loop Loop. As with the drum machine, audio feedback may not be immediate, because it depends on the loop within which the system sequentially reads each side of the Mix cube. The user must join the Instrument cube and the Mix cube to transfer a sound, but this sound is only played the next time the system reads the corresponding side of the Mix cube. This makes it hard for the students to associate a sound to a cube or to an action. As discussed before, the visual representation of the loop on the Mix cube's screen is too subtle and quite complex, so it did not help students to manage the timed audio feedback. In addition, when many sounds are added to the Mix cube and one of them is excluded, the difference in the perceived sound is hardly noticeable. Collectively, these factors make the link between action and effect difficult to establish, especially for children with intellectual disabilities. None of the students could understand how to create a piece of music with Loop Loop. An example is shown below:

> Sounds play and then stop. The boys look to the two cubes each one is holding. They don't know how the sounds were produced.
> *Irvin:* ***how do you play these?***
> The sounds play again, within the loop, and the **boys immediately look up to the researcher, as if the researcher was doing something to play the sounds**.
> *Researcher* [laughing]: *I'm not doing anything, don't look at me!*
> The boys laugh as well.
> *Irvin:* ***how do you do it?***

As a result, students used a variety of actions and experimented with several spatial configurations, believing they were controlling the sounds in these ways, which seemed more intuitive to them than joining two particular cubes. Interaction became a process of students performing random actions and producing sounds by chance, as can be clearly seen in the following excerpt:

> Nick places **all four cubes together**. Sounds play and the students look at each other and smile happily. Then Nick puts **all of them apart** again and the sounds stop. Michaela takes two of the cubes, and puts them together, and Nick does the same with the other two cubes. Sounds play again but students don't know who is producing them. **Nick takes one cube from Michaela and joins it to his cubes**. **Michaela joins the last cube to the group** (forming a square) and many sounds play.

The other two activities with the Sifteo cubes were of a very different nature. In both of them, there was immediate digital feedback. The Do the Sift game was based on a straightforward action-effect relationship: the game told the user which action to perform with each cube, and gave immediate visual and audio feedback indicating correct or incorrect action. Once the students understood the rules, they were able to engage in this action-effect based game following the step-by-step instructions. It did not consist, however, of an exploratory context.

In the screen saver activity, the squares on the screens reacted both to movement performed by the students, and to proximity of other cubes. These two factors together created a more complex causality, although feedback was immediate. However, such complex causality did not seem to hinder students' interaction, and they could manage both phenomena, as shown in the excerpts and Figure 8.24 below.

As soon as the activity starts, the students move the blocks in their hands.
*Bernard: oh yeah, **they fall over.***
*Alicia: **they move**, look.*
Alicia shakes the blocks. They join the blocks in different arrangements.
*Bernard: **they magnify, together.***
Alicia: oh yeah!
(...)
Alicia: Bernard, Bernard, let's put them all together
Bernard accepts, and they make a square together, with the four cubes.
*Bernard: wait, wait, **what are they doing**...*
Alicia: wow...
The **squares get rearranged due to proximity** of the cubes and the children enjoy it. Then Bernard **takes the four cubes and 'flies' them together in the air**.

Figure 8.24: Bernard 'flies' the Sifteo cubes together while both students watch the screens

Researcher: so have a little play with them, see what they do.
Each girl takes one cube. They shake, tilt and touch the screen with their fingers.
*Donna: **it's moving about**.*
Researcher: what about the other two [cubes]*?*
Each girl takes another cube, but then they place the first ones on the table to investigate the new one. They do the same kind of actions.
*Donna: **it's playing about or something**.*
Diane holds both cubes and moves them, but quickly puts one back on the table.
Researcher: so what do you think they're doing? Do they work on their own?
Diane: no...
Researcher: what happens?

Diane: ***They all stick together****.*

The excerpts show that although the squares on the screens behaved according to two different action-effect mappings, there was clear feedback and students could perceive both behaviours.

Overall, these results are aligned with the literature on mappings and intuitiveness, with time and location figuring among the main aspects of 'natural coupling' (Wensveen, Djajadiningrat and Overbeeke, 2004). For all systems, analysis showed that temporal contiguity was the principal and most important design factor for children's comprehension of action-effect mappings, and subsequent productive interaction. Providing immediate, clear feedback for students' actions was crucial for supporting them in exploring the systems. Simple causality also contributed to this clear mapping, although cases like Sifteo screen saver showed that some complexity in causality (dependence on more than an action or object) may be introduced in interaction without hindering exploration. Nevertheless, complex causality must be evaluated carefully at design time, in terms of intellectually disabled students' comprehension of the mappings.

Guideline D9: Action-effect mappings should be contiguous in time: immediately subsequent feedback should be provided for user actions.

Guideline D10: In action-effects mappings preference should be given to simple causality based on students' actions.

Since it is not always feasible to guarantee simple causality only from design, particularly in collaborative settings, where interference commonly happens, the role of the educator becomes crucial to facilitate the perception of causality.

Guideline F4: When simultaneous actions and/or digital effects occur in interaction, the educator should facilitate the learner's perception of causality by isolating action-effect couplings.

Spatial contiguity is another important factor for action-effect mappings. However, as this interacts with issues around the different types of representations and how they are physically or digitally coupled in space, it is discussed in detail in the following section.

Coupling between representations

Besides the clear link between what users do and what happens in response, physical and digital representations in tangible systems should be seemingly naturally coupled (Hornecker and Buur, 2006). The coupling between physical representations and underlying digital information is a central characteristic of tangibles (Ullmer and Ishii, 2001) that has been highlighted in several frameworks. However, the perceived coupling between physical and digital representations is not always straightforward (Price, Sheridan and Pontual Falcão, 2010). A central question is how to make the links between the physical and the digital intelligible for users. Broadly speaking, representations in general should be appropriately integrated for learners to reach a deeper understanding (Kaput, 1989). Integrating multiple representations is not a new topic and is known to be challenging for education, as it can be a complex process for learners to interpret representations individually, translate between them (Ainsworth, 1999) and establish semantic mappings which may not be obvious (Scaife and Rogers, 2005). In particular, the transience of dynamic representations like tangible systems' can be even more complex for cognition, raising issues of increased memory load and subsequent impact on students' inferences, multidimensionality (Price, 2002), and meaningful mappings between physical interaction and abstract conception (Clements, 1999).

The properties of the links between physical and digital representations influence the extent to which they are perceived as a same entity or as two separate but connected objects, which Koleva et al. call *level of coherence* (Koleva et al., 2003). A very well known taxonomy of tangible systems, coined by Fishkin, discusses coupling of representations according to two dimensions: *metaphor* and *embodiment* (Fishkin, 2004). Although the term 'embodiment' has been largely employed and discussed in other contexts and with other meanings, as presented throughout this thesis, for Fishkin embodiment refers to the extent to which users perceive the digital effects as being embodied within a particular physical representation. So Fishkin classifies embodiment in four levels of physical distance between input and output events, namely: 'full', when both input and output are coincident in place, i.e. represented by the same device; 'nearby', when input and output are close in physical space;

‘environmental’, when the output is around the input device; and ‘distant’, when it is relatively far, like in another screen or even another room (Fishkin, 2004). Although Fishkin’s taxonomy became very popular in the tangibles field, its parameters of embodiment are rather subjective: the difference between ‘close’ and ‘around’, for example, is not clear-cut. Price’s category of *location*, which also refers to the distance in space between physical and digital representations in tangible systems, is clearer in this respect (Price et al., 2008). In Price’s framework, ‘embedded location’ corresponds to Fishkin’s full embodiment, with coincident input and output. Or, if input and output are contiguous, representations are ‘co-located’; and finally, if there is separate physical input and digital output, then location is ‘discrete’. While Price acknowledges that location has an impact for cognition in terms of making links between object, action and representation, but does not explicitly express a priori preference for either type of location (Price et al., 2008), Fishkin suggests that designers should aim at full embodiment as much as possible, in order to maximise the user experience of full direct manipulation (Fishkin, 2004), thus creating the impression of unified physical-digital objects (Shaer and Hornecker, 2010).

Previous work has investigated the effect of co-located and discrete locations with typically developing children (Price et al., 2009; Price, Sheridan and Pontual Falcão, 2010). Location was found to influence children’s ability to interact effectively with the system and with each other, mainly with regard to the locus of attention and awareness of others’ actions. Action-effect mappings were less clear for discrete location design, particularly for users interacting simultaneously. In this sense, results of studies with intellectually disabled students were not different from typically developing. Comparing the coupling of representations across the tangible systems used in the present studies revealed how co-located and embedded configurations, or, in Fishkin’s terms, full and nearby embodiment, worked best for children's comprehension of the systems and establishment of action-effect mappings.

In the interactive tabletop, digital effects are co-located with the physical objects, in a restricted area. This area becomes the simulation environment, where objects must be placed and where ‘everything happens’. In other words, the surface, where input and output are coupled, provides a ‘frame’ for the simulation environment, tying physical objects and digital effects together. There is one (broad) focus of attention only, helping to keep children concentrated on the activity, and also making the action-effect mapping clearer. Figure 8.25 below shows students interacting with the tabletop, where they could see the digital effects contiguous to the physical objects that were placed on the surface.

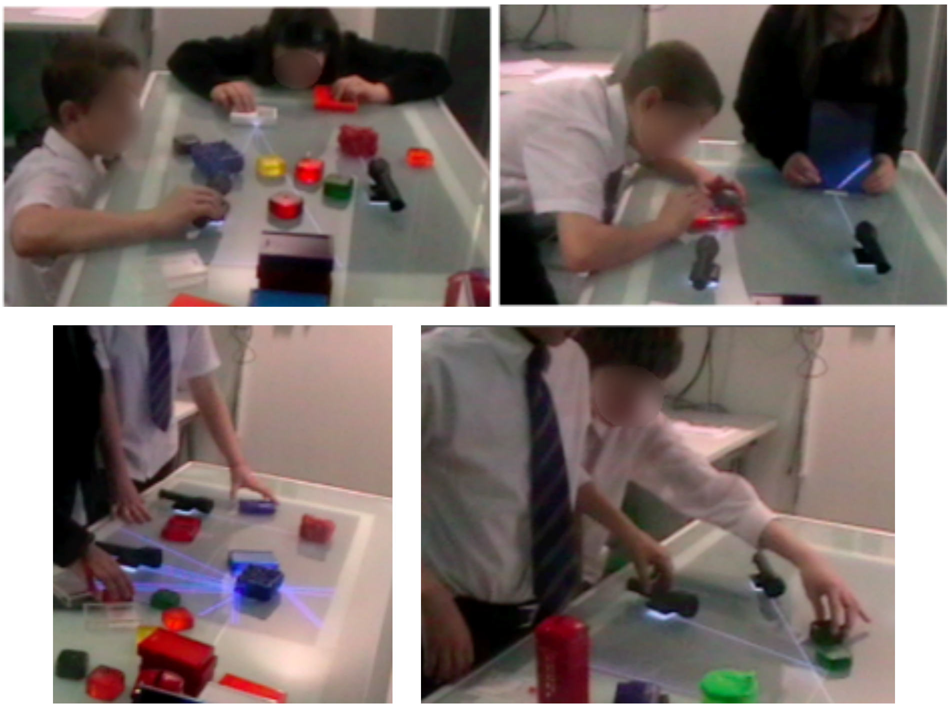


Figure 8.25: Contiguous digital effects on the tabletop, coupled with physical representations

The images show how students' attention was focused on the interactive space, where representations were naturally coupled. As discussed in Chapter 7, there is no distance between interaction instrument and conceptual object, characterising truly direct manipulation.

Truly direct manipulation was also the case of the augmented object. It was characterised by full embodiment or embedded location: the digital effects correspondent to the response of the object to students' actions were embedded in the physical object itself (the LEDs that produced the lights were literally inside the container). This means that the object was simultaneously the input and output device, making this distinction meaningless. Students could explore the object by moving it, and observe the consequences *on the object itself*. Immediate feedback and coupled input and output made the action-effect link clear, which facilitated exploration.

In the case of the Sifteo cubes, visual and audio representations were differently coupled to physical objects. All visuals, for the three applications, were displayed on the cubes' screen, configuring an embedded location, or full embodiment. In the case of the screen saver, the squares on the screens reacted to the movement *of the own cubes*, and to proximity of other cubes. In the Do the Sift game, the actions indicated on the cube's screen had to be performed with the very same cube, so there was a tight coupling of representations and truly direct manipulation. If a cube displayed 'shake', the user had to shake that specific cube. The students needed some time to understand the rules of the game, but then the coupling between the representations, and between their actions and the outputs, were clear, as shown in the excerpt below:

> *Researcher: so with this one, you just have to do what it says on the bricks, can you see what it says on the bricks?*
> *David: do the 'shift'*
> *John: sift*
> *David: sh- sift*
> The boys move the cubes around as they try to find out what to do.
> *David: oh, I get it, I get it. You have to move that one.*
> *John: no, that goes on that, that goes on that, see?* [John lines up the cubes].
> The game starts.
> *Researcher: Excellent! Well done, now it's gonna give you something different to do.*
> *John* [reading]*: don't move*
> Boys don't know what to do. David moves one of the cubes, but loses.
> *Researcher: oh, what did it say?*
> *John: don't move?*
> Another round starts.
> ***John: oh… press****.*
> **John presses the cube**. Boys line up all cubes as another round starts.
> *David: I don't really get this.*
> *Researcher: you just have to do what's on the bricks. What does that one say, at the end?*
> ***David: stand***
> *Researcher: so can you do that with the brick?*
> ***David: oooh***
> **David stands the cube**.
> *David* [reading]*: neighbour all.*
> *John lines up the cubes.*
> ***David: oh, this is easy now****.*
> *Boys: press, press, press.*
> The boys go on playing, performing each action. They take turns to perform the actions.

The passage above illustrates that once John and David understood the rules of the games, each one in their own time, they found it “easy” and engage in independent play.

Do the Sift also had audio representations, which were not as tightly coupled to the physical cubes. Since the cubes do not have speakers, all audio representations in the Sifteo system are transmitted by the computer that is running the software. The physical distance between the cubes and the source of the sounds, therefore, depends on the distance between the place where the users interact with the cubes and the location of the computer. This characterises discrete location, because sounds come from a separate source. Fishkin classifies audio output as environmental embodiment, as the output happens around the input devices. In the case of Do the Sift, such decoupling of representations did not negatively interfere with interaction, because the application was predominantly visual and the sounds were just an additional effect to reinforce the main, visual information shown on the cubes. The sound effects of Do the Sift were short signals and alerts that typically constitute audio feedback in digital systems, and were not aimed to represent specific content. In addition, the sounds were continuous: there was a game soundtrack, plus special audio effects for right/wrong actions. The students concentrated on the visuals, did not pay much attention to the audio effects, as they were ‘always there’, and were not disturbed by the fact that the sounds were coming from elsewhere (Figure 8.26).

Figure 8.26: Students’ focus of attention on the cubes when playing Do the Sift, despite the sounds that were coming from the computer at the other side of the table

Loop Loop represented a different scenario. The sounds were not continuous in the background - but played in a loop as added to the Mix cube by the students. In addition, the sounds were played every time the Preview cube was joined with the Instrument cube. All sounds were thus produced according to students’ choices. In this case, it was more problematic that the sounds did not come from the cubes themselves but from the computer speakers, because this increased the difficulty for students to build action-effect links, as the sounds they were producing *with the cubes* were emitted by *another device*. An example is shown in Figure 8.27 below. As the boys explore Loop Loop, one of them transfers a sound to the Mix cube without noticing. After a time lag, sounds are played and the students are very surprised, as the expression in their faces show (blurred in the image to preserve children's anonymity). They look up immediately, getting distracted from the visual representations, because the sounds do not come from the cubes.

Figure 8.27: Boys immediately look away from the cubes as a sound is played

In situations like this, which were recurrent with Loop Loop, students did perceive the sounds - differently from the lack of perception discussed previously, mainly related to the drum machine. Nevertheless, the use of audio was still problematic due to the decoupled representations. "Our ears tell our eyes where to look", says Brewster - an interesting sound from outside someone's view makes the person turn their attention to it seeking more information (Brewster, 2002, p. 4). In the present context, this represented a decoupling between two complementary representations that needed to be integrated for meaning making. The playing interface of acoustic instruments is often integrated with the sound source; for example, in the case of a violin, the strings are part of the control and the sound generation mechanisms. It is different with electronic musical interfaces: the interface and control mechanism are usually completely separate from the sound source. So the mapping (or relationship) between control (input actions) and sound production (output responses) is more difficult to establish, and thus must be defined explicitly (Antle, Droumeva and Corness, 2008). In the present studies, this was particularly problematic because students did not know which cube was responsible for producing the sounds, in each situation. If the sounds were emitted from the cubes themselves, the students might have been able to understand better how to control the system, and what the functions of each cube were.

Also being an electronic musical interface, the drum machine presented a very similar problem to Loop Loop. Audio feedback was also given through the speakers of the computer running the software. Although the speakers were next to the interactive surface, the sounds did not come from the 'visible parts' of the system, i.e. the blocks or the interactive surface. So, the sounds seemed a *separate* entity, which, for the students, was not necessarily connected to the blocks they were manipulating. As with Loop Loop, such decoupling added to the difficulty of building an action-effect link with the drum machine.

In summary, the studies with the children with intellectual disabilities clearly showed that embedded and co-located input/output favoured students' comprehension of the systems, putting them more in control, and helping to establish action-effect relationships.

> Guideline D11: Input and output events should be contiguous or coincident in space to increase comprehension of action-effect mappings.

Table 8.4 sums up the tangibles' characteristics in terms of representational mappings. Shadowed cells indicate characteristics found to be positive for students with intellectual disabilities.

	Temporal contiguity	**Spatial contiguity**	**Causality**
Tabletop	Immediate	Co-located	Simple / Complex (secondary)
Augmented object	Immediate	Coincident	Simple
Sifteo's screen saver	Immediate	Coincident	Simple / Complex (secondary)
Sifteo's Do the Sift	Immediate	Coincident / Separate (secondary)	Simple
Sifteo's Loop Loop	Delayed	Separate	Complex
Drum machine	Delayed	Separate	Complex

Table 8.4: Representational mappings of the tangibles

Conceptual metaphors

With the appearance of GUIs, metaphors became the basis of interface design (Dourish, 2001). According to Dourish, "metaphor is such a rich model for conveying ideas that it is quite natural that it should be incorporated into the design of user interfaces" (2001, p. 143). One of the most common stated purposes of tangibility is that such interfaces provide 'natural' mappings that employ spatial analogies and adhere to cultural standards, capitalising on people's familiarity with the real world (Shaer and Hornecker, 2010). An important issue to note is that meaning does not reside in the representations used in the system themselves, but in the ways they are manipulated and interpreted (Dourish, 2001). Therefore, meaning attached to artefacts by designers is not necessarily transparent to students, nor interpreted by them as the designer predicted (Meira, 1998). Using artefacts and understanding their significance interact in the construction of knowledge within the learning process (Lave and Wenger, 1991), and thus it is important to study the use of the artefacts in contexts of practice and how they are transformed by the students (Meira, 1998). This section analyses how students conceptually interpreted the elements of each of the four tangible artefacts used in the empirical studies and which characteristics of the tangible systems were key for students' interaction.

A key aspect of the concept of tangible technologies is that the physical components of the system are objects of interest, with associated meanings relevant to the context (Ullmer and Ishii, 2001). As discussed in Chapter 4, tangible systems are typically designed based on space multiplexing, i.e. they employ multiple objects simultaneously, able to represent different functions or entities. However, symbolic information does not always have an obvious physical equivalent (Klemmer, Hartmann and Takayama, 2006). Several frameworks attempt to organise and classify the types of links between physical objects and their conceptual meanings. Holmquist et al. taxonomy suggests three categories of physical objects in terms of how they represent digital information: containers (generic objects that can be associated with any type of digital information); tools (used to actively manipulate digital information, usually by representing some kind of computational function); and tokens (physical objects that resemble the information they represent in some way, and thus are closely tied to it). Tokens are thus the only category where there is a relationship between physical appearance and associated digital information (Holmquist, Redström and Ljungstrand, 1999).

This thesis takes a more educational perspective to analyse metaphors in tangible systems. In this sense, Antle proposes that physical-digital *semantic* mappings should be analysed in the context of children's comprehension of things in various representational forms, considering the reciprocal nature of physical and mental representations (Antle, 2007). Price et al. discuss the metaphors involved in tangible systems in terms of 'correspondence' (Price et al., 2008). Of particular interest here is 'physical correspondence', which refers to mappings between physical properties of the objects and learning concepts. Physical correspondence is symbolic when the object has little or no characteristics of the entity it represents; and literal when the object's physical properties are closely mapped to the object it is representing.

The tangible tabletop was designed based on literal physical correspondence: all interaction objects have a role in the simulation that is identical to their role in the 'real world', i.e. a green, smooth, opaque block has in the system the physical properties of a green, smooth, opaque block, and nothing else. The digital effects illustrate real phenomena that occur with such objects in the physical world, but that are not visible to the human eye, e.g. a green light beam being reflected off a green block (which is why an object is seen as green, but the process of reflection is not naturally visible in the physical world). The digital simulation of the tabletop is thus based on the physical characteristics of each interaction device, which have persistent individual behaviours. Such persistence enables taking advantage of shape, size and position of physical devices, as they are dedicated in form and appearance to a particular function or digital data (Shaer and Hornecker, 2010).

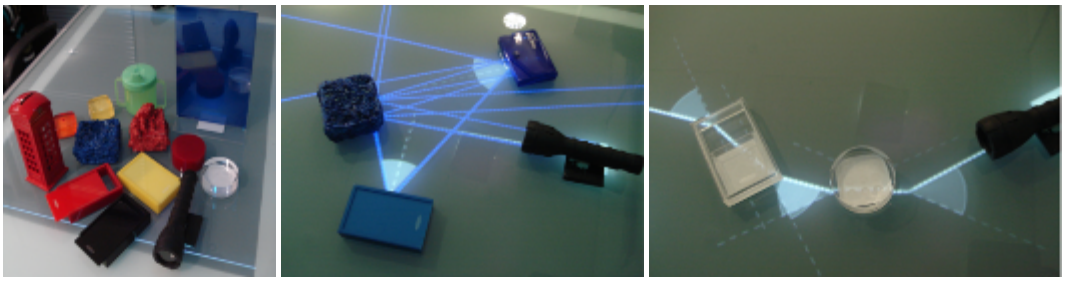


Figure 8.28: Different shapes, materials and colours of the tabletop objects (left) and the effects some of them produce (centre and right)

Physical characteristics of the objects in the tabletop system, for being very concrete and appealing to the senses, like colour, material, texture and shape (Figure 8.28), were generally well perceived by the students, and their practical consequences in the simulation were learned throughout interaction, as shown in the excerpts below:

> *Researcher: and are they all the same, these objects, do they all behave the same?*
> *John: no*
> *David: yes*
> *Researcher: what's the difference between this one that you're holding now* [the transparent cardholder]
> *David:* ***this is plastic, that's rock*** [one of the blocks]*.*
> *Researcher: and when you put it on the table, does it behave the same?*
> *John: no,* ***it changes colour***

> *Researcher: why do you think this blue object over there* [the rough object] *is making a different effect?*
> *David:* ***because it's a different material****.*
> *Researcher: yeah! So what does it do, this different material?*
> David places a red opaque object on the light beam.
> *John: huh… I don't know* [picking up the rough object]*. Maybe it's because there's loads of bits of blue… and it's reflecting over the bits, it makes loads… different, like…* [pointing to the reflected beams in many directions]*.*
> David places a green opaque object on one of the torch's beams. John sees it and picks it up to add to his explanation.
> *John: whereas the green, it's only like…* ***it got nothing*** [showing the smooth surface with his hands]*,* ***it's just one colour****…*
> John picks up the rough blue object again.
> *John: this is the same colour, but* ***it's got… all over the place, different blues****. And when you put it on there, there's loads of it,* ***like it is on the material.***

However, perceiving the physical properties of the materials did not mean that students understood the underlying concepts related to the physics of light. In his analysis of the Illuminating Light system, which is closely related to the tangible tabletop, Dourish identified various levels of embodied interaction where multiple levels of meaning could be associated with the objects and their manipulation. According to Dourish, a user might move the physical devices just as objects, to see what happens, clear them out of the way, and so on. Or, they might choose to move the icons as mirrors and lenses, i.e. as the metaphorical objects that they represent in the simulation space. Yet in another level, these metaphorical objects can be used as tools in another domain (laser holography), and thought of as, for instance, virtual mirrors with the function of redirecting a virtual beam of light (Dourish, 2001). In the tabletop studies, students with intellectual difficulties, for most of the interaction, remained at the first level of embodied interaction, using 'the physical devices just as objects, to see what happens'. The excerpt below typically represents the kind of dialogues and interaction that predominated in the studies. Figure 8.29 illustrates highlighted passages of the excerpt.

> Lionel points a second torch to the blue rough object and **boys enjoy the effects, as both torches point to it**.
> *Derick: oh look at this, it shines both sides.*
> Lionel walks to the object area and chooses a different object, the red rectangular object with a hole. **He places it on the surface and points the torch to it**. He notices the spectrum of colours.
> *Lionel: look! Multicolour.*
> Both boys observe for a couple of seconds. Derick **places a yellow block on the white beam**. Lionel moves it to another white beam. Then Lionel puts the yellow block inside the red object's hole, and points the torch to it.
> *Lionel: let's put this in here.*
> Boys observe but nothing different happens.
> *Derick: let's shine it on the blue now.*

Figure 8.29: Boys engage in manipulating objects but make no associations with the conceptual domain

The excerpt shows how the boys were concentrated on producing a variety of effects and exploring the system, but with no spontaneous conceptual links with the domain of physics of light. Previous studies with the tabletop have shown that spontaneous engagement with the concepts did occur during interaction of typically developing children of similar ages with the tabletop (Price and Pontual Falcão, 2011). However, students with intellectual disabilities had great difficulty in transferring the concepts conveyed by the system to the physical world: even when they understood the rules involved in the interaction between the objects, they did not associate them with what happens in the physical world with such objects. In other words, they were not able to generalise and take concepts to 'another level' of abstraction. In addition, a drawback of the tabletop prototype is the paper tag (fiducial), necessary for the camera to recognise each object. Objects had to be placed with these markers facing the surface. The markers caught the students' attention, as can be seen in the excerpts below, for being unfamiliar symbols. The students (correctly) associated them with the technical functioning of the system, but this made students focus on technical aspects instead of conceptual ideas. In other words, when asked for explanations about the phenomena observed, students were not able to separate technical aspects from conceptual aspects, and used both interchangeably, as shown below:

> *Researcher: so what do you think is happening there, can you tell me what you found out?*
> *Bob: what I think is happening* [picks an object and shows fiducial]*, **because of this laser**, it's going through it and it's like… this little thing in there will… like… maybe there's all colours in there, and when this touches it, light… they've gone to there* [placing object on surface] *and then just like…*
> *Emma: it takes all the colours and like… **they try to form the colours of this*** [an object] *on to there* [the surface]*, and **make the colour**… **they're like sensors**.*
> *Researcher: and what do you think this is about? What is it trying to show you, or teach you?*
> *Bob: **It's trying to show you here that you can form like really good patterns of colours**.*

> Researcher asks the girls what they found out so far and what they think is happening in the system. The girls hesitate.
> *Donna: when you put this* [holds the torch] *on, it's like… **a line is like coming through that way*** [makes the action to demonstrate – her hand goes along the light beam]*… and every time you move it… it like… it goes like… hum**… left and right*** [moving her hands to demonstrate].
> *Researcher: and when it hits an object, what happens?*
> *Donna: well, when you put this* [pointing to a red rectangular object] *on, **the line goes red… because the object is red.***

The excerpts show that students' explanations for what the simulation was showing were mostly technical and pragmatic descriptions of what they observed, and not abstractions and generalisations of concepts. Students could describe what was happening in terms of 'lines' and colours, but grounded in very specific, concrete instances observed (i.e. they could say that a *red* line comes out of a *red* object, but did not say sentences like "an object produces a line of its own colour", for example). This relates to known difficulties with abstraction and generalisation of children with intellectual disabilities discussed in Chapter 2, and Vygotsky's example of a child who knows they have ten fingers in their hands, but is not able to guess how many fingers another person has - in other words they cannot extract from a concrete object a corresponding sign to be applied to a collection of objects in the same class (Vygotsky and Luria, 1993).

The tabletop system was the only one, among the four tangible systems used, that simulated a real-world situation, with literal physical correspondence. In the drum machine system, the physical form of the objects did not hold any metaphorical correspondence to the conceptual object (percussive sounds produced). In other words, there was a distance between the interaction instruments and the conceptual object: the set of interaction devices were controllers for the abstract object of sound. In addition, the physical devices were equally and generically shaped, and their appearance did not indicate their meaning or function: according to the d-touch designers (Costanza et al., 2011), the objects could be *anything*, provided they were tagged with the symbols shown in Figure 8.30, and they served as tools to trigger sounds. The interactive area did not have an associated conceptual metaphor either - it simply was a graphical arrangement to enable the mappings between position and sounds, and thus allow the user to compose music. So, there were no visual associations with a real drum machine or the types of sounds it can produce: representations were all very abstract. For the students, the piece of paper and blocks were not meaningful: they could not relate them to what they knew from their experiences in life with music.

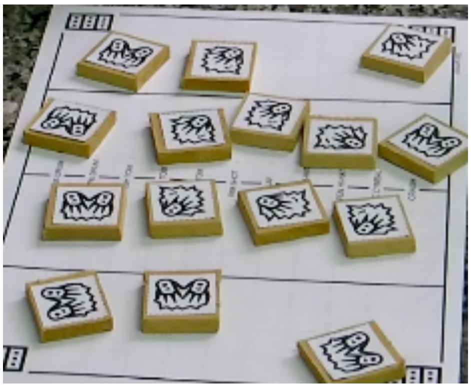


Figure 8.30: The drum machine's physical components

Another important drawback was the fact that meaning was embedded in the devices' position in the interactive area and not in their shape or appearance, i.e. the sounds played were determined by the presence of blocks in specific locations. Sounds were mapped to positions of objects but *not to the objects per se*. Students were not able to understand such mapping, nor that the blocks *did not carry meaning*, but were just triggers for the sounds according to where they were placed. Students rather thought that the sounds depended on each block, i.e. to produce a sound of cymbal, for example, one had to place a specific block on the surface, because that block was the trigger for that sound. The excerpt and Figure 8.31 below illustrate the mapping between sounds and blocks made by the students:

Researcher: Are the sounds all the same?
Andrew: No
Researcher: Why do you think there are different sounds?
Andrew: because of the blocks…
Researcher: Right… what if… let's try something here.
The researcher takes all the blocks away by pushing them with her hand to the side. All sounds stop.
Researcher: Let's see if it stops… has it stopped? Yes… So, if I put one block here. Let's see… [Researcher places a block on the surface]. *If I ask you now to* ***produce a sound different from the one I did****, how could you do this?*
Andrew: ***another block.***
Researcher: Another block? And where would you put it?
Andrew places a block very near the researcher's block.

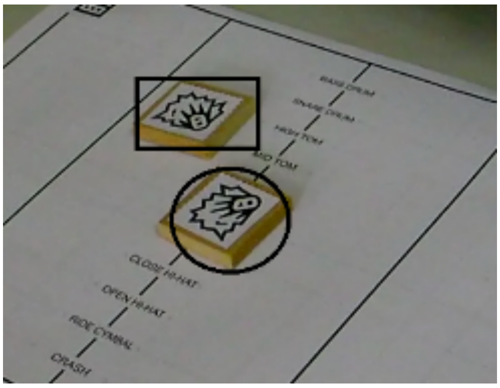


Figure 8.31: Block placed by Andrew (marked with circle) when asked to produce a different sound from the one produced by researcher with block marked with rectangle

Loop Loop, the other musical application used in the studies, also had cubes as controllers of sounds, the difference being that they were not mere control devices. In fact, each cube did carry a meaning and had a specific role in the process of composing music. This should have helped students to establish more meaningful mappings than in the case of the completely abstract drum machine's interaction devices, however, it proved not sufficient. Loop Loop's physical correspondence was symbolic: the Sifteo cubes are equally and generically shaped and do not exploit physical properties, such as shape or size, to convey meaning. Meaning was conveyed through visual representations in the cubes' embedded screen, but because all cubes were physically identical, it was very hard for the students to perceive them as having completely different functions and behaviours. So, despite the visual representations on screen, the children still manipulated them as if they had the same behaviour, showing no signs of perceiving differences in meaning between the cubes, but rather dealing with them as identical components of an assembly kit. An illustrative example is given below:

Researcher: Do you like to make music? We'll try to make a bit of music with the blocks. So, I'm going to explain to you how it works.
Researcher explains and demonstrates with the cubes. Paul does not concentrate for very long during the explanation. After finishing the explanation, the researcher suggests that the boys try to make some music. Nathan **joins one of the cubes with the cube Paul is holding**.
Paul: use that…
Nathan **joins his two cubes in different ways, and joins one cube with Paul's**. Sounds are played now and then. **Nathan takes all three cubes and tries different spatial configurations**. **Paul shakes a cube**. **Boys press the cubes** (which pauses the system).
Researcher: tell me when you've finished your tune and we'll listen to your tune.
Nathan tries quickly **many different ways of joining the cubes**.

In addition, even though the cubes had different roles, a conceptual distance between the interaction devices and the conceptual object existed: in Loop Loop cubes did not represent the sounds themselves - two of them (the Instrument cubes and the Mix cube) could be seen, at most, as containers of several different sounds. It must be acknowledged that sounds do not have obvious physical counterparts, making the design of audio-based systems much more complex in relation to conceptual metaphors.

In the case of the other two Sifteo applications (screen saver and Do the Sift), the interaction objects coincided with the conceptual objects. For example, in Do the Sift, when a cube showed the instruction 'shake', students had to shake that specific cube, which was not meant to represent anything but itself. With this instruction-based game, students engaged in doing as told with no questioning about the meanings of the elements of the system. In the case of the screen saver, the cubes also had their own behaviours and did not metaphorically represent other entities. They were artificially created representations that did not aim to illustrate a specific conceptual domain like the tabletop simulation, or to link to real world objects. When interacting with the screen saver, some students came up with their own theories in an effort to connect with previous knowledge and familiar contexts, as illustrated by the excerpts below:

> *Bernard: What are they?*
> *Researcher: they're called Sifteo cubes. What can you see happening there?*
> *Bernard: it's got squares, all reacting as real cubes would be if they were inside in it. They're like rolling around.* ***Except they would be rolling in 3D if there were real, now they're rolling in 2D.***
> Alicia is shaking her blocks as Bernard talks. She hums a song.
> *Researcher: What do you think, Alicia?*
> Alicia keeps her eyes down and plays with the cubes.
> *Alicia: it's got* ***magnets*** *there...*
> She moves the cubes, joining them.
> *Alicia:* ***are they magical?***

> *Irvin: I've got this... hum...* ***this television****... hum... they're little, they're like this, like* ***magnet things****, and you turn them on and you see like this person doing...*
> *Researcher: is it like a videogame?*
> *Irvin: it's* ***a small TV****, like, the size of... a bit bigger.*

The augmented object did not simulate situations of a specific conceptual domain either, although this had been the original intention of its design.

Initially, the object was meant to provide visual representations that would clearly map to phases of movement of a physical object, and in this manner help students to understand concepts related to movement. However, due to technical limitations of eliciting meaningful data from the accelerometers, the resulting effects were not as clear as expected (periods of acceleration and deceleration produced by a human hand with the object were too short to be noticed). The design was then adapted to focus on object positioning, mapping it to colours. The augmented object embodied its own representation, it was not meant to stand for something else, so there was no distance between interaction instrument and conceptual object. It did not build on conceptual metaphors and it simply was an object to be explored on its own right. The augmented object's shape was generic and had no specific associated meaning from the real world. However, the feedback from the embedded lights provided an abstract mapping that related to positioning, adding another dimension to the object's behaviour.

Students' comprehension of the object's behaviour concentrated on the fact that it "changed colour" (clear action-effect mapping), but it was hard for them to go beyond this in terms of establishing specific mappings between position and colour. This relates again to these students' difficulties to generalise and build abstract theories from concrete instances. Although they knew that they could produce different colours by moving the object and changing its position, they were unable to articulate general rules such as "if you put the object with the lid down, it will show green". So students were aware of the action-effect mapping, but did not easily establish the conceptual rules of the system, as shown below:

> *Researcher: what do you think it's happening, what is it that you do that is affecting it?*
> *Diane: moving it.*
> *Donna: and controlling, how you move it.*
> *Researcher: so how do you move it to control?*
> *Donna:* ***well, it's like… huh… I don't know*** [giggles and looks at Diane]

> *Researcher: so why do you think it's changing in that way?*
> *Diane: because we're doing the movement?*
> *Researcher: so what do you think your movement is doing then? Are there certain kinds of movement?*
> *Donna:* ***there could be… I don't know… yeah, it's like we're controlling it by touching it, maybe…***

In an effort to find explanations for the object's behaviour, as happened with the Sifteo screen saver, students came up with a variety of theories: "is it like a mood bracelet?"; "so do you talk at it?"; "the air, when moving the object, makes it change colour"; "it changes colour when it sees the special thing"; "there's a sensor, and then when you press, when you put your thumb on it, and take it off, it changes colour"; "oh, I know! It looks like this ball, at soccer time"; "a kind of lamp"; "it's like a disco". A recurrent theory among the students was that when the object was pointed somewhere, it captured the colour of whichever thing it was pointing to. Figure 8.32 illustrates students testing this theory.

Figure 8.32: Students point object to different things to check if it changes colour accordingly

The generic shape of the augmented object seemed to give children freedom to create their own metaphors and try to make associations with real life, trying to find out what the object meant, through a combination of previous knowledge and 'magical thought'. Similar findings were reported with Chromarium: according to the authors, children seemed to understand that there were causal links between the representations and their actions, though explanations that were "a mix of magical thought with bits of previous knowledge" (Gabrielli et al., 2001, p. 11). Indeed, interface metaphors often carry some tension between literalism and magic (Smith, 1987) because digital technologies allow combining realistic simulation with more abstract formalisms (Scaife and Rogers, 2005), and computational referents have capabilities that metaphorical objects do not. Therefore, there is a moment when the metaphorical vehicle is abandoned and 'magic', or the extra power of the digital technologies, takes over (Dourish, 2001). On one hand, this breakdown in correspondence to the real world can be seen as an advantage provided by digital technology (Grudin, 1989), for aggregating extra capabilities; on the other hand, in educational systems it can lead to misunderstandings and confusion in the learning process (Price and Pontual Falcão, 2009). This discussion however is out of the scope of this thesis. Here, creation of theories, being magical or more realistic, is seen as a very positive sign of students' exploratory behaviour, as will be discussed in the next chapter.

To conclude, analysis has shown the importance, for students with intellectual disabilities, of providing connections with familiar contexts and the physical world through the systems' representations, particularly by taking advantage of physical properties. The most straightforward way to do this would be designing for literal physical correspondence, as in the case of the tabletop simulation. But, if physical representations do not hold such strong metaphorical links to the conceptual objects, which indeed is not always possible, they should at least evoke familiar concepts from children's world (as in the case of the augmented object and the Sifteo cubes). Completely abstract representations like the drum machine's, with no metaphorical correspondence to the conceptual domain, and highly unfamiliar representations, led to poor results in comprehension and exploration. It is important to say that literal physical correspondence or strong metaphorical links do not guarantee students' comprehension of underlying concepts, as it has been shown with the tabletop simulation. This relates to students' difficulties with abstraction and generalisation, a detailed analysis of which demands future studies. More importantly here, is how to best design tangible systems in order to encourage students' independent exploration. Within this context, conceptual metaphors that capitalise on physical properties and on familiarity with the students' world have proved to be highly recommended.

> Guideline D12: Representations should make metaphorical references to the conceptual domain, building on objects' physical properties and evoking links with the physical world.

Summary

This chapter presented a holistic analysis of the interaction between children with intellectual disabilities and four different tangible interfaces. Findings fall into the following themes: types of digital representations; physical affordances; representational mappings; and conceptual metaphors. Tangibles are, by definition, hybrid systems composed of digital and physical representations, and both kinds emerged in the analysis as having important contributions for child-tangible interaction in the context of intellectual disabilities. Among the three types of digital representations (textual, auditory and visual) present in the tangible systems used in the empirical studies, visual was found to be the most adequate form of representation for children with intellectual disabilities. Visual representations were found to naturally attract students' attention, leading to engagement in interaction, while auditory representations were less easily perceived, and texts presented a barrier for most of the students, because they could not read.

The physical counterparts of tangibles were also found to have an influence on a range of interactional aspects. Firstly, confusion was identified that was caused by the physical objects' perceived, culturally constructed affordances, which although physically apparent were not part of the system's designed interaction. The consequence of this was students repeatedly engaging in actions that were not meaningful within the systems' scenarios, and that could become disruptive and/ or confusing, particularly in the context of intellectual disabilities, hindering productive exploration. Therefore, ideally, affordances that invite actions that do not have meaningful results should not be apparent - or, all physical affordances should lead to consistent, meaningful actions, or at least to non-disruptive ones. Spatiality is another characteristic of tangible systems related to physical affordances. Based on the observation that students spontaneously tended to build a variety of spatial arrangements with the systems' physical objects - and expected such arrangements to possess meaning in the systems - the recommendation is to capitalise on spatial configurations when designing tangibles for children with intellectual disabilities, and to provide feedback that clearly counters expectations on the physical properties of objects, if they are not part of the system's design. A third aspect of physical affordances relates to different roles that actions performed with the artefacts may have. The analysis in this case was less focused on the design of the systems, being more about learning opportunities that may arise from child-tangible interaction for: (i) acquiring concepts through imitation of actions of others (capitalising on these students' tendency to mimic what others do); (ii) physically communicating ideas instead of having to do this verbally (as for children with intellectual disabilities oral expression is often hard); (iii) spontaneously engaging in actions to explore the systems with no fear of 'getting it wrong' (helping to overcome self-confidence issues).

A third emerging theme refers to mappings between the diverse representations of the systems. Of utmost importance for children's comprehension of the functioning of the systems and the associated concepts is the establishment of proper action-effect mappings, and adequate intrinsic feedback, i.e. clear relationships between what the child does and what happens in the system *as a consequence*. In terms of design, to help students with intellectual disabilities establish such mappings, temporal and spatial contiguity of actions and effects are recommended. In other words, system feedback should preferably be simultaneous or immediately subsequent to actions, and input and output events should be co-located or coincident in space, rather than occur in separate locations. In addition, cause-effect links should be clear, which can be obtained by using a design based on simple causality.

Finally, analysis has shown the importance of designing physical-digital semantic mappings that capitalise on conceptual metaphors related to children's familiar contexts, rather than using more abstract representations. Such metaphorical connections, preferably building on physical properties, contribute to children's comprehension and facilitate their exploration of the systems.

Overall evaluation of the tangibles

Table 8.5 summarises the tangibles' key aspects identified in regard to intellectually disabled students' exploratory interaction, according to the analysis presented in this chapter. Shaded cells indicate positive characteristics, i.e. found to encourage children's exploration and facilitate their comprehension. The table shows that from all tangibles analysed, the interactive tabletop presented ideal characteristics for all aspects considered. It is therefore a system that offers a potentially stimulating environment for children with intellectual disabilities to engage in discovery learning. For this reason, the empirical sessions with the tabletop were analysed in more detail, focusing on how such characteristics encourage discovery (Chapter 9).

	Main digital represen-tation	**Spatial configurations**	**Temporal contiguity**	**Spatial contiguity**	**Causality**	**Conceptual metaphors**
Tabletop	Visual	Meaningful	Immediate	Co-located	Simple (& complex - secondary)	Yes
Augmented object	Visual	Not applicable	Immediate	Coincident	Simple	No
Sifteo's screen saver	Visual	Meaningful	Immediate	Coincident	Simple (& complex - secondary)	No
Sifteo's Do the Sift	Visual	Meaningful in one case only	Immediate	Coincident (& separate -secondary)	Simple	No
Sifteo's Loop Loop	Auditory	Meaningless	Delayed	Separate	Complex	No
Drum machine	Auditory	Meaningful	Delayed	Separate	Complex	No

Table 8.5: Key characteristics of tangibles for intellectually disabled students' interaction

Chapter 9 - Discovery learning with the tangible tabletop and the role of guidance

Chapter 8 took a broad perspective to analyse tangible interaction for children with intellectual disabilities and identify characteristics of tangibles that could support exploration. Analysis within four broad emerging themes (types of digital representations, physical affordances, representational mappings, and conceptual metaphors) indicated that, among the four tangibles used, the interactive tabletop possessed ideal characteristics to foster exploration for children with intellectual disabilities. With the goal of further investigating this finding, this chapter presents a focused analysis of particularities of tangible interaction and external facilitation as mediators of processes of discovery. More specifically, a quantitative analysis is presented of free versus guided conditions of child-tabletop interaction, examining how specific interactional characteristics contributed to produce distinct cognitive outcomes of discovery learning. The analysis also addresses the initial hypothesis of this work that the free exploration condition could be more productive in terms of discovery learning, when supported by the constitutive characteristics of tangible interfaces, as presented in Chapter 8.

As discussed in Chapter 2, discovery learning is anchored in constructivist theories, and is characterised by not directly providing the target information or conceptual understanding to the learner, who must find it by conducting investigations with the available materials (Alfieri et al., 2011; Bruner, 1961). However, there are concerns that leaving students to unstructured self-discovery can lead to errors, misconceptions, confusion and frustration (Alfieri et al., 2011; Kozulin, 2003), that learners' cognitive workspace may be overwhelmed, and opportunities for knowledge construction not occur (Alfieri et al., 2011). On the other hand, direct instruction methods can be ineffective when they discourage learners from actively making sense of materials (Mayer, 2004). In addition, children with intellectual disabilities have difficulties in understanding instructions (Cawley and Parmar, 2001), which makes it harder for them to learn via the direct method.

To address the problematic lack of structure while maintaining the pedagogical benefits of the constructivist approach, guided discovery methods propose the use of techniques like feedback and scaffolding to introduce some degree of guidance found to be advantageous (Alfieri et al., 2011; Shulman and Keisler, 1966). This should help to reach the ideal envisioned by Bruner in his discovery learning theory (Bruner, 1961): give students enough freedom to become cognitively active in the process of sense making, and enough guidance to construct useful knowledge (Mayer, 2004). Nevertheless, one of the great challenges of teaching by guided discovery is to know how much and what kind of guidance to provide (Mayer, 2004). One of the main reasons for the failure of discovery learning strategies is the lack of sufficient feedback from the materials themselves (Alfieri et al., 2011). Alfieri et al. (2011) suggest that the debate on issues of unassisted versus assisted forms of discovery should move towards a discussion of how scaffolding is best implemented and how to provide feedback. This is particularly important in the case of students with intellectual disabilities, for whom, on one hand, discovery learning activities are recommended, and on the other hand, lack of structure is even more challenging (Scruggs et al., 1993). Tangible technologies, as shown in Chapter 8, have the potential of providing a substantial amount of feedback and scaffolding within exploratory, hands-on contexts.

What constitutes discovery?

In processes of exploration, students encounter genuine situations of experience that make them spontaneously engaged in reflection. Exploring can be seen as the process of sensing the problem, observing the conditions, elaborating a conclusion, and testing it through active experimentation (Dewey, 2001). In other words, exploration is the "intentional endeavour to *discover specific connections* between *something that we do* and the *consequences which result*" (Dewey, 2001, p. 151, emphasis added).

'Discovery' in the present analysis refers to three types of cognitive outcomes: (i) understanding how to interact with the system; (ii) acquiring literal comprehension about the scenarios represented by the system; and (iii) reaching conclusions related to the conceptual domain. Children who participated in the empirical studies had no previous knowledge about the functioning of the tangibles. They were not trained because observing how intuitive and accessible the systems were was one of the goals of the analysis. A short introduction was given at the beginning of the sessions to minimally guide the children to start interaction, but students needed to learn how to use the symbolic system that was presented (Kozulin, 2003), initially through 'uncontrolled' attempts that lacked planning (Vygotsky, 1978). They tried different actions without knowing what to expect, so as to form their ideas about the interface and how to interact with it. Such ideas constituted the first type of discovery, as shown in the example below:

> Emma places the orange block on the beam, with the fiducial facing up.
> *Emma* [flipping object so that fiducial faces down]: ***won't work if it's that way.***

This type of discovery does not refer to how the technology per se functions, i.e. that a camera underneath the table reads the fiducials and a projector displays the visual effects. Focus on the technology in this sense was considered counterproductive in this analysis, given that the research interest was on conceptual understanding. 'How the system works' was a type of discovery necessary for allowing children to interact with the system, knowing that they needed to place the objects with the fiducial on the surface, use the torch as the source of visual effects, point torch to objects to produce the visual effects, and so on.

The second type of discovery refers to tentative interpretations of the behaviour of the elements of the system, but at the level of 'literal' comprehension. When acquiring literal comprehension, students become able to make plans, build and test hypotheses, and pursue goals. In the process of trying, they find things that do what they had anticipated, or, in other words, things that 'work', or happen 'as they should do' (Dewey, 2001). The method that led to each achievement is learned, and adopted for following attempts (Dewey, 2001). What characterises the second type of discovery is that although students take actions based on their process of reflection, their thinking is related to practical and technical aspects of the system, and not to the conceptual domain that the artefact is designed to represent. Vygotsky names this type of concept 'spontaneous' and ‘empirical’ (Kozulin, 2003). Although empirically rich, such concepts are often contradictory and immature, as children reason in terms of specific instances of objects, and do not generalise to the concepts of the ‘real world’ represented (Piaget, 1970). Literal comprehension with the tangible tabletop is easily perceived through vocabulary like ‘lines’ (instead of light beams), ‘circles’ (instead of angles), among others. However, literal comprehension does not necessarily need to be verbalised, and can be identified through students’ visible activity, as in the excerpt below. In the initial part of the session, Kale experiments with all types of red objects to find out they all consistently produce red beams.

> *Kale: wait, let me… ah, here is a better one.*
> Kale replaces the **rough object** for a **red opaque block**. A single red beam is shown. Kale replaces the red block for the **red phone box**. A single red beam is shown.
> *Jason: just put one thing down!*
> Kale tries **yet another red object (the one with the lid).** A single red beam is shown.
> *Jason: just put one thing!*

The third type of discovery refers to students’ ability to transfer the system’s representations to the physical world, making generalisations from the specific instances of the interface. They reach a conceptual level of comprehension, and they no longer think in literal and specific terms, but about general world phenomena. This corresponds to Piaget’s conceptual knowledge, which includes and goes beyond practical knowledge. For Piaget, conceptual knowledge emerges from empirical / practical knowledge through reflective abstraction, leading to awareness of conceptual relations (Piaget, 1974). For Vygotsky, this is the domain of conceptualisation and systematic reasoning, corresponding to the development of scientific processes (Kozulin, 2003). This type of comprehension was rare and incipient in the studies with children with intellectual disabilities. Different from literal comprehension, which can be perceived through actions performed by the students and the forms they manipulate the system, it is much harder to identify conceptual comprehension other than through verbal statements. This type of discovery was identified through the use of vocabulary linked to the conceptual domain like ‘reflection’, ‘beam’, ‘light’, etc, and generalisations like the one illustrated below:

> *Emma: but with the white* [moves the blue filter to the white beam] *it turns blue… through it…*
> *Researcher: so why do you think it turns blue through this one, and not the other ones?*
> *Emma: I think that…* ***with all the different colours… if it doesn't match, it will block the lights***.

It is important to add that no judgement was made here on the accuracy of children's interpretations, i.e. if their conclusions were correct or incorrect. Students' achievement of making a discovery with the support of the technology was, per se, considered positive in the context of this work, which focused on how tangible interaction supported exploration rather than on the creation of misconceptions in discovery learning activities.

Children's interaction with the tangible tabletop was guided by discovery, but not without obstacles in the way. Typically, obstacles are part of the learning process, and thus not necessarily negative. Problems that emerge in learning situations should be stimuli for thought. One of the key factors for successful discovery learning is that information needed to deal with these problems should be available and used in the process of developing and applying solutions (Dewey, 2001). The excerpt below shows a situation where obstacles were overcome, and helped in building up discovery:

> *Derick: Oh, let's try this!!* [picking blue filter up]
> Lionel takes the blue filter from Derick and places it on the surface. He points the torch to it and leans to see the surface on the other side. However **the filter is placed too near the edge to be recognised by the camera, and no effects are shown**.
> *Derick**: well, that's not interesting**.*
> *Lionel* [moving the filter]***: maybe if you move it…***
> **As Lionel moves the filter, the camera recognises it and a blue beam is shown on the table.**
> *Lionel:* ***oh, there you go!***
> *Derick: that is cool. It's like sensor lights, innit.*

Nevertheless, there were situations in chid-tangible interaction where obstacles were too great to serve as stimuli and instead led to *disruption*, here defined as an interruption of an exploratory path, with consequent change in the flow of interaction. Disruption made children abandon a specific investigation. While episodes of discovery ended in some conclusion that represented a take-away for the students, disrupted episodes were ended with no apparent lesson learned. An example is shown in the excerpt below:

> Charlotte places the black wallet on the surface, and tries rotating it, regardless of the torch that lies on the surface, and the beam of light produced by it. No visual effects are shown. She drags the wallet a little on the surface, and Fatima moves the torch. At one point the **beam from the torch is blocked by the wallet**, but **the girls do not react to it and Charlotte puts the wallet away**.

Within the context of discovery learning of children with intellectual disabilities with tangible technologies, the analysis aimed to answer three specific questions regarding the cognitive outcomes produced (considering free and guided conditions):

1. Which type of cognitive outcome from discovery was most frequent?
2. Which aspects of child-tangible interaction contributed most for discovery?
3. Which interactional obstacles were the main causes of disruption?

Method

A coding scheme was developed to investigate how specific interactional characteristics of tangibles led to the cognitive outcomes explained above, answering the three stated questions, in the context of free and guided conditions.

Procedure

Coding was applied to video transcripts of tabletop sessions, which described actions, dialogues, and status of the system. Coding procedure consisted of, first of all, breaking the text of the transcripts into coding units. Coding units were defined as conceptual chunks that represented a situation of exploration, which typically comprised a short *sequence of actions* deeply related and based on the system's *consequent effects*, along with related *verbal utterances*, if any. A coding unit with this structure typically ended up in one of the cognitive outcomes aforementioned. An example of a coding unit is shown below, where discovery referred to constructing literal comprehension about the behaviour of transparent objects:

> Lionel tries a transparent block on a blue beam **[ACTION]**, and the beam goes through the object **[EFFECT]**. Then he places the transparent block between the torch and the rough blue object **[ACTION]**. Beams of light are refracted by the transparent object, and a representation of angles of refraction is shown **[EFFECT]**.

Lionel: oh sick!! Circles! **[DISCOVERY]**

A coding unit could also be a situation prematurely ended by *disruption*, as explained previously. In the passage below, disruption is caused by confusion from perceived affordances: Lionel tries to use the torch in the 3D space, pointing it to two objects combined, but as there is no feedback he abandons his investigation.

Derick places a yellow block on the white beam **[ACTION]**. It reflects yellow **[EFFECT]**. Lionel moves it to another white beam **[ACTION]**. It reflects yellow **[EFFECT]**. Then Lionel puts the yellow block inside the red object's hole **[ACTION]**, and points the torch to it **[ACTION]**.
Lionel: let's put this in here.
Boys observe but nothing different happens **[DISRUPTION]**.
[end of coding unit]
Derick: let's shine it on the blue now.

Each coding unit was classified as an episode of discovery of one of the three types described in the previous section, or as an episode of disruption, as depicted in Table 9.1.

Cognitive outcome	Characteristics
Discovery of type 1 - How the system works	Students find out how to interact with the system, e.g. place objects with the fiducial on the surface; point torch to objects to produce effects; rotate objects to control direction of light, etc.
Discovery of type 2 - Literal comprehension	Students discover how objects behave, e.g. pointing the torch to a red object produces red 'lines'; the blue rough object produces many blue 'lines' which 'go different ways'; etc.
Discovery of type 3 - Conceptual comprehension	Students make general conclusions about the phenomena and/or use vocabulary of the conceptual domain, e.g. "the red objects reflect red"; "this [angle] is like what we did in Maths"; "it's like sensor lights"; etc.
Disruption	The flow of interaction is interrupted or changed, which impedes making a discovery.

Table 9.1: Characteristics of the cognitive outcomes represented by the coding units

In addition to the classification above, each episode was also coded according to a coding scheme (Table 9.2) based on the categories discussed in Chapter 8, with adaptations. The categories of the coding scheme refer to characteristics of the tangible tabletop as well as behaviours and actions enabled by affordances of the system.

Category of analysis	Code
Physical affordances	**Confusion from perceived affordance**
	Physical characteristic (of object)
	Action as imitation
	Action as communication
	Action as exploration
	Action as revision
Action-effect mappings	**Informational feedback**
	Non-informational feedback
	Extrinsic feedback
	Interference
Technical aspects	**Technical constraint**
	Engagement with technology

Table 9.2: Coding scheme for aspects of tangible interaction and exploration

Physical affordances

- *Confusion from perceived affordances* corresponds to the subcategory discussed in Chapter 8, relating to contexts where students tried to use the interaction objects as they would do in the physical world, e.g. manipulating the torch in the 3D space.
- *Physical characteristic* refers to characteristics of the physical elements of the system. In the case of the tabletop, the objects varied in colour, shape, size and texture.
- *Actions* taken by the students were coded according to the three roles discussed in Chapter 8: *imitating* others; *communicating* with others e.g. giving an answer or demonstration; and *exploring* the system by manipulating the objects. The extra code *Action as revision* was added for situations where an action was taken as a direct follow-up to a previous action, and based on the system's feedback. This code was added due to the focus on the process of discovery learning, where the

relationship between subsequent actions is key to build up the cognitive outcome.

Action-effect mappings

The subcategory of action-effect mappings was considered too broad as a code, and was broken into more specific topics.

- *Informational feedback* comprises the characteristics, discussed in Chapter 8, of temporal and spatial contiguity between physical and digital representations, allied to visual digital representations. These characteristics were grouped for constituting the typical intrinsic feedback given by the tabletop, thus always occurring simultaneously.
- *Non-informational feedback* refers to digital feedback that basically consisted of interruption of current events or lack of production of new events. This code was added due to the situations discussed in Chapter 8 where the design choices for conveying feedback were not perceived or not understood by the children, e.g. illustrating absorption of light by interrupting the beam.
- *Extrinsic feedback* refers to interventions of the facilitator in the interaction, like giving hints or explanations. This type of feedback was at times solicited by the students, spontaneously given by the facilitator in guided sessions, or occasionally provided in free sessions when intrinsic feedback of the tabletop was perceived as not sufficient for engaging the students in productive discovery learning.
- *Interference* is a form of complex causality, which refers to action taken by one student that has consequences for other students' interaction and / or for the current arrangement displayed on the table, thus affecting students' interpretation about what is happening in the system (as discussed in Chapter 8). Although interference is normally associated with negative effects, in the context studied it can also engender productive exploration (Pontual Falcão and Price, 2011).

Technical aspects

This category was especially created for this coding scheme, in order to accommodate situations related to dealing with the technology.

- *Technical constraint* refers to limitations of the technology (such as the need for the paper marker to be facing down, and placed on a specific area of the surface), hardware constraints, or software bugs that interfered with children's interaction.
- *Engagement with technology* refers to situations where students focused on trying to understand the technical functioning of the system. Although this can be considered a type of exploration that is not necessarily negative (Price and Pontual Falcão, 2011), in this work it is considered a distraction. Being analysed in the context of discovery learning, exploration in this thesis refers to the process of investigating the system's scenarios, and ultimately comprehend the underlying learning concepts. This does not, therefore, include technical investigation, or understanding how the technologies work. In contrast to previous work (Price and Pontual Falcão, 2011), engagement with the technology is considered as hindering conceptual exploration.

Through an iterative process of analysis, these categories were found to be aspects of child-tangible interaction that played a key role in the process of discovery, either encouraging or hindering it. A coding unit was typically tagged with several codes that illustrated the aspects involved in the 'story' of that episode of exploration. A priori, the same code could, in distinct situations, vary between being positive or negative for supporting discovery. For example, interference could distract and/or confuse a student, preventing them from pursuing their process of discovery and even causing disruption. Or, interference could make a student realise some phenomenon that was not apparent before, thus leading to discovery. So, for each code applied to the text, a plus sign or minus sign was added to indicate if that aspect was encouraging (+) or hindering (-) exploration towards discovery. However, by their own definition, the codes tended to be mostly positive or negative. For example, informational feedback is expected to be positive, while technical constraints tend to hinder exploration. In the case of episodes that culminated in discovery, codes indicated the aspects that helped building up discovery in the process of exploration, and the obstacles that were overcome. For the episodes that ended by disruption, the codes revealed the obstacle(s) that caused the interruption of investigation.

As explained in Chapter 7, sessions with the interactive tabletop were of two kinds: (i) free, with very low level of guidance, where the facilitator set a general goal to be explored and gave eventual help on an if-needed basis; and (ii) guided, consisting of structured sessions where the facilitator guided students through step-by-step tasks. These two conditions were set to investigate the effectiveness of the feedback given by tangible interaction versus the level of external support needed for productive exploration. Although the researcher also asked reflective questions at the end of free sessions (as described in the studies' procedure - Chapter 7), which engendered further actions from the children, this final part of the activity was not included in the free sessions' analysis, as the procedure in these last moments resembled guided sessions due to the researcher's intervention.

Although the three questions posed about the contributors and obstacles for discovery could be answered by counting instances of the codes, a sound comparison between the free and guided conditions could only be made through a statistical test to normalise the data corpus. Two-step cluster analysis was performed in the Statistical Package for Social Sciences™ (SPSS) software with the aims of (i) verifying natural groupings within data to check if free and exploratory sessions were significantly distinct; (ii) validating the statistical significance of the results that compared the contributions of the interactional characteristics coded in free and exploratory conditions.

The basic algorithmic procedure compares several possible clusters according to the chosen probabilistic criterion, balancing the best clusters and the optimal number of clusters. The two steps of the procedure are: 1. Pre-clustering of data in the greatest possible number of small sub-clusters. These small clusters, being numerous, will have only a moderate degree of dissimilarity. 2. Second order clustering from the pre-clustering performed previously, merging sub-clusters with higher similarity, until an optimal number of clusters is reached. An optimal number of clusters corresponds to the smallest possible number of clusters with the greatest distance among them, i.e. few groups very different from one another.

As cluster analysis can reveal clusters that are not necessarily apparent from direct or sequential inspection, it was used to perform multidimensional grouping of categorical nominal variables, and thus verify if specific interactional characteristics were aggregated with free or guided conditions, indicating that they had a more important role in one or the other. For example, cluster analysis could reveal a clustering of the variable 'Action as imitation' with free sessions, indicating that without external facilitation, children tended to resort more to imitating their peer.

Measures

Coding was applied to 12 groups, being 6 from free sessions and 6 from guided sessions, and produced a total of 273 coding units, distributed as shown in Table 9.3.

FREE sessions		GUIDED sessions	
Groups	Coding units	Groups	Coding units
F1	22	G1	23
F2	12	G2	27
F3	15	G3	13
F4	30	G4	30
F5	18	G5	28
F6	33	G6	22
Total of coding units in free sessions: 130		Total of coding units in guided sessions: 143	
Total of coding units: 130 + 143 = 273			

Table 9.3: Distribution of coding units

All occurrences of codes were counted, in free and guided sessions, and according to the cognitive outcomes of each episode. For the cluster analysis all episodes were numbered from 1 to 273, and were labelled with the corresponding group of students; the type of session (free or guided); and the cognitive outcome (Table 9.1). The other variables were the codes of the coding scheme (Table 9.2) - these were coded according to their occurrences per episode (0, 1, or more than 2 occurrences).

There are different proximity measures to be used in cluster analysis. Here, chi-squared test was used to test the null hypothesis that the frequency distribution of the variables in the data set is a product of random chance. The probability of a distribution obtained by chance, established by chi-square (p-value), must be less or equal to 5% for refuting the null hypothesis. Fair and good cluster quality indicate that the probability of the null hypothesis validity was less or equal to 0.05, and thus can be refuted.

Results

Cluster analysis identified two clusters of identical size (136), with fair cluster quality (Figure 9.1). Type of session was the most important predictor, with importance 1.00, indicating a very significant difference between free and guided sessions. Results are thus discussed assuming a statistically significant data separation in two clusters representing free and guided sessions.

Figure 9.1: Cluster quality
Source: SPSS

Nine variables were classified as relevant predictors in the comparison between free and guided sessions. They are presented in Table 9.4 and discussed in the next sections.

Predictor	Importance
Type of session (free or guided)	1.00
Extrinsic feedback	0.14
Action as communication	0.08
Engagement with technology	0.05
Cognitive outcome of episode (discovery of type 1, 2 or 3)	0.04
Technical constraint	0.04
Informational feedback	0.03
Confusion from perceived affordances	0.02
Action as exploration	0.02

Table 9.4: Relevant predictors of cluster analysis

Cognitive outcomes of episodes

As depicted in Table 9.1, episodes could generate one of three types of discovery (how the system works, literal comprehension, and conceptual comprehension), or end in disruption. A simple count of episodes, transformed in percentage to account for the difference in number of episodes of each type of session (Table 9.3), shows a clear predominance of discovery of type 2 (literal comprehension of the system) in both types of sessions, being higher in guided sessions (Figure 9.2). Cluster analysis confirmed this predominance, indicating 'Cognitive outcome of episodes' as a relevant predictor for clustering, although of moderate importance (0.04), being 'Discovery of type 2 - literal comprehension' the most frequent category (39.7% in the free sessions cluster and 58.1% in the guided sessions cluster). Cross tabulation of type of sessions and cognitive outcomes also showed the relationship between guided sessions and discovery of type 2, and the predominance of discovery of type 1 and disruption in free sessions. Although the null hypothesis p-value for this cross tabulation was 0.06 (>0.05 and thus not significant; chi-square=7.409; df[6]=3), the proximity of the obtained p-value to the significance level, within a more flexible quantitative approach, allows to assume that differences in occurrences of types of cognitive outcomes, between free and guided sessions, are worth a discussion, presented later.

[6] Degrees of freedom (df) correspond to the number of values of a variable that can vary, being an important parameter in hypothesis testing statistics like chi-square.

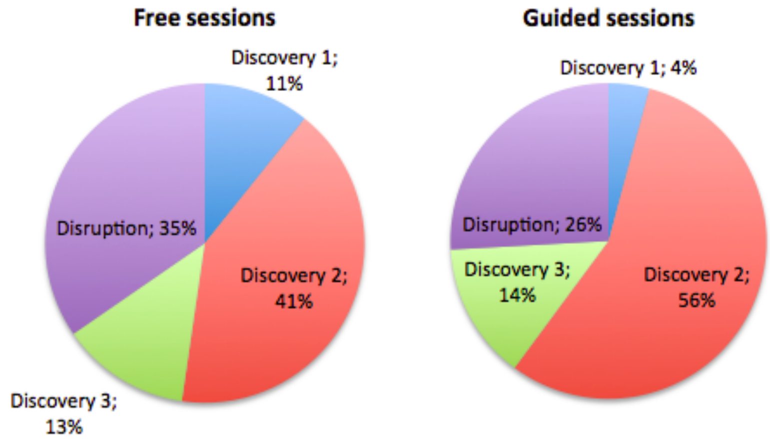


Figure 9.2: Cognitive outcomes of episodes in free and guided sessions

Contributing aspects for discovery

Eight of the twelve codes were found in episodes of discovery, i.e. were considered to encourage and support children with intellectual disabilities in the process of discovery learning. They were the same codes for free and guided sessions (Figures 9.3 and 9.4). The four major contributors coincided for free and guided sessions, with one difference in the ordering only, between action as exploration and physical characteristic. In free sessions (Figure 9.3), the major contributors were, respectively: 1) informational feedback; 2) action as exploration; 3) physical characteristic; and 4) action as revision. In guided sessions (Figure 9.4), the major contributors were, respectively: 1) informational feedback; 2) physical characteristic; 3) action as exploration; and 4) action as revision.

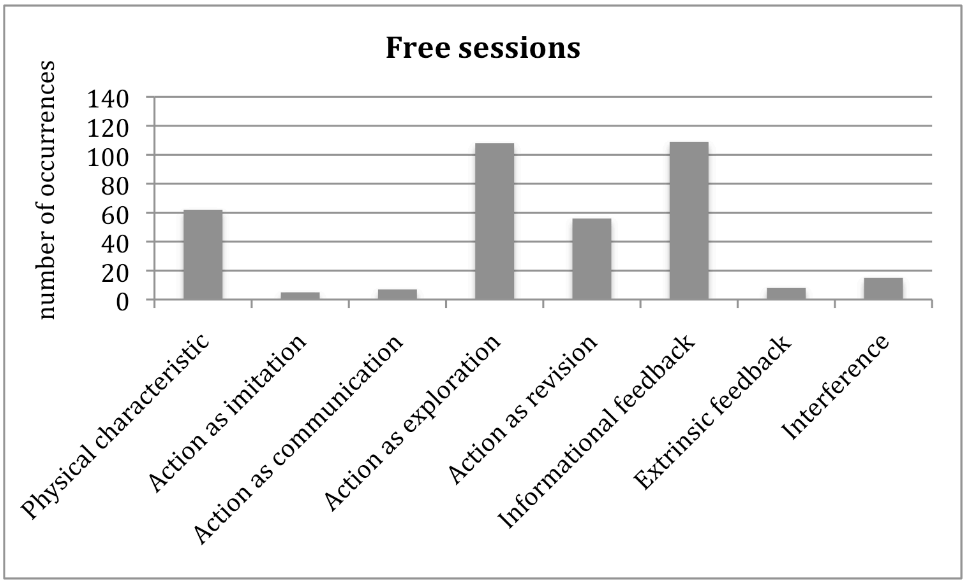


Figure 9.3: Contributing aspects for discovery in free sessions

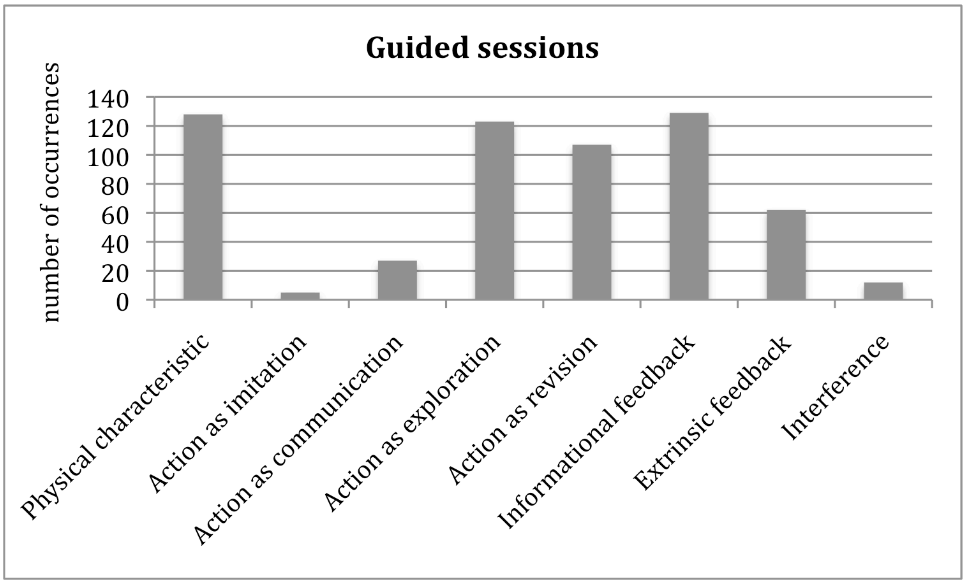


Figure 9.4: Contributing aspects for discovery in guided sessions

Among all contributors, cluster analysis indicated four as relevant predictors for differentiating between free and guided sessions. Action as exploration (importance 0.02) was found to be predominant in free sessions. Extrinsic feedback (importance 0.14), action as communication (importance 0.08) and informational feedback (importance 0.03) were found to be predominant in guided sessions. In particular, strong statistically significant relationship was found by cross tabulation between: (i) type of sessions (=guided) and action as communication (chi-square=15.889; df=2; p=.000); (ii) type of sessions (=guided) and extrinsic feedback (chi-square=35.713; df=2; p=.000).

Causes of disruption

Five of the twelve codes were found to contribute for disruption. They were the same codes for free and guided sessions (Figures 9.5 and 9.6). Non-informational feedback was the top obstacle in both types of sessions. In free sessions (Figure 9.5), it was followed by confusion from perceived affordances, interference and technical constraint with almost the same amount of occurrences. In guided sessions (Figure 9.6), it was followed by engagement with technology and technical constraint.

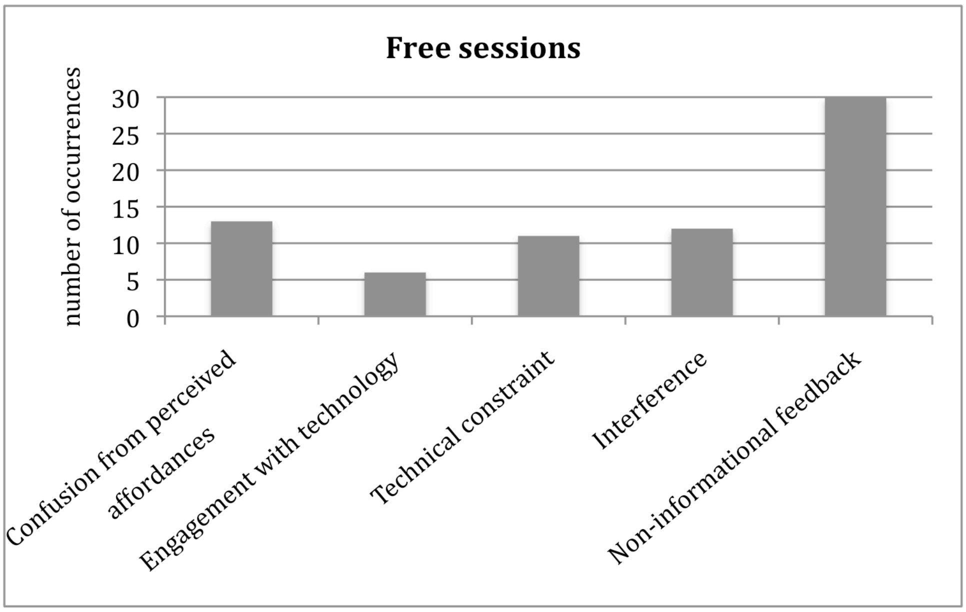


Figure 9.5: Causes of disruption in free sessions

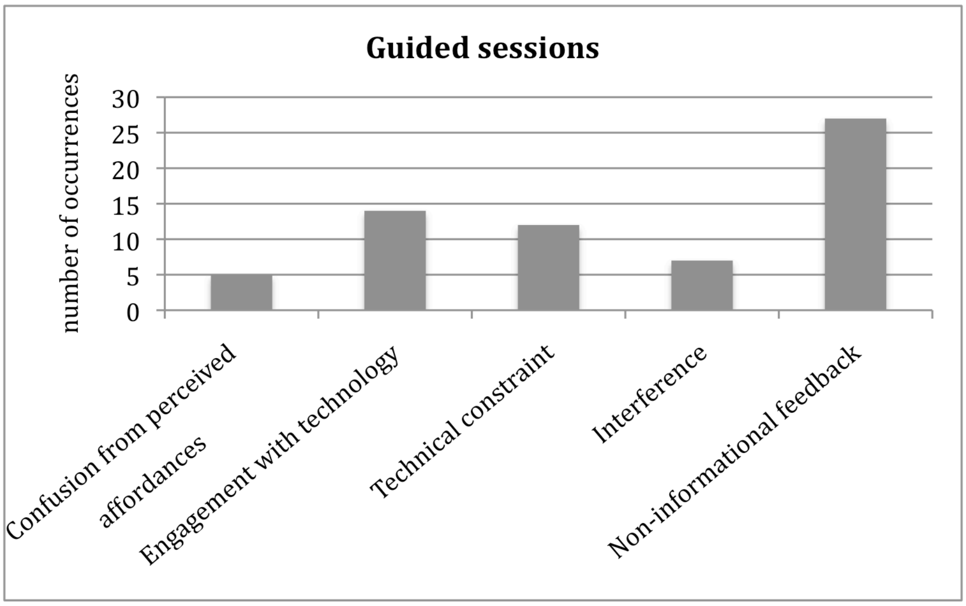


Figure 9.6: Causes of disruption in guided sessions

Cluster analysis indicated three obstacles as statistically significant for comparing free and guided sessions: engagement with technology (importance 0.05), technical constraint (importance 0.04) and confusion from perceived affordances (importance 0.02) were considered predominant in free sessions.

Discussion

In both free and guided sessions, discoveries of type 2 were the most frequent type of episode, followed by disruption, discovery of type 3, and lastly discovery of type 1. Discoveries of type 1 (how the system works) being the least frequent cognitive outcome can be explained by the fact that in all sessions the facilitator gave a brief introductory explanation about the system to help students start the interaction - i.e. if they were able to understand the explanation, they did not have to make discoveries of this kind on their own. In addition, in guided sessions, help to use the system was also given during interaction, which justifies the smaller value for this type of discovery.

Discoveries of type 3, which represent the ultimate learning objective of the activity, had rather low occurrence in both types of sessions. Nevertheless, this must be analysed in the context of Piaget's reflective abstraction (Piaget, 1974) and Vygotsky's theory on the development of scientific processes (Kozulin, 2003), discussed previously. Ideally, in discovery learning, conceptual knowledge *emerges from* empirical / pragmatic knowledge through reflective abstraction (Piaget, 1974), but this process is not straightforward and only takes place when the child has reached a mature level of development of empirical concepts (Vygotsky, 1986). The low occurrence of discoveries of type 3 is not surprising, and their appearance, although timid, is a positive indication of the value of tangible interaction. Conceptualisation from experience is known to be an even harder process for students who are intellectually disabled (Bay et al., 1992). Indeed, previous studies (Price and Pontual Falcão, 2011) with typically developing students interacting with the tabletop have showed higher levels of engagement with concepts than found in the present work. The cited study found that, during tabletop interaction, children aged 11 to 14 years predominantly engaged with the conceptual domain (spontaneously - 28% of the time; or being prompted - 34%), when compared to engaging in tangential activity (i.e. understanding the underlying rules of system behaviour) (25%) and with the technology (13%). However the analysis of two different age groups revealed that younger children (11-12 years) engaged more in tangential activity (29%) than spontaneously engaged with the learning domain (18%), although they still engaged more with the concepts when prompted by a facilitator (34% of the time). This establishes an interesting relationship with the present work, considering that children with intellectual disabilities' cognitive development often corresponds to a lower chronological age, and also suggests the importance of external guidance for increasing the amount of attention paid to the learning concept, despite the scaffolding provided by tangible technologies.

Other factors also come into play when analysing the number of occurrences of conceptual discoveries, like type of facilitation, possible inadequacy of the content for the students' ability, unfamiliar setting and technology, and length of sessions. The latter in particular influences the maturation of children's development of spontaneous concepts. As children with intellectual disabilities require more time and repetition to understand the systems and develop conceptual comprehension, the length of sessions dedicated to the activities becomes more relevant. On the other hand, the concentration span of these children is shorter, so the best trade-off seems to be running series of repeated, short sessions.

Conceptual discovery, however, is not the only kind of episode considered productive. The three types of cognitive outcomes discussed here were seen as positive, as discoveries of type 1 and 2 lay the basis for future conceptual discoveries. From Chi's perspective, in constructivist learning activities learners not only engage in the learning task (e.g., by manipulating objects) but also construct ideas that surpass the presented information (Chi, 2009), which occurred in all types of discovery. In other words, all episodes of discovery were considered constructive rather than only active (Chi, 2009). This relates to previous conclusions on how typically developed students' engagement with tangential activity in the tabletop environment provided a constructive foundation for promoting engagement with domain concepts (Price and Pontual Falcão, 2011).

Such understanding of the underlying rules of system behaviour were coded here as discovery of type 2, and were the most frequent cognitive outcome. By acquiring a literal comprehension of how the objects behaved in the simulation and learning the rules, children gained control over the system, increasing their confidence and engagement. The predominance of discovery of type 2 in guided sessions, in contrast with the predominance of 'action as exploration' in free sessions contradicts initial hypotheses of this work that (i) free exploratory interaction could give *more opportunity* for the children to come up with their own conclusions rather than following the facilitator's instructions and answering questions; (ii) a less structured environment could make children feel safer to give their opinions, than when they are expected to solve a specific task. The main reason for having considered such hypotheses lay on the expectation that dynamics, interactivity and physicality of tangible systems would make children engage with the content even in more independent, exploratory interaction. In other words, such characteristics of tangible technologies should allow introducing more meaningful scaffolding and feedback within exploratory contexts, helping to guide children towards productive discovery, and thus addressing the problem of finding the optimal balance of hands-on learning and structured activities, faced in special education.

However, the predominance of action as exploration in free sessions, in contrast with the predominance of discoveries of type 2 in guided sessions, reinforces Chi's (2009) and Alfieri et al. (2011) arguments that engagement in hands-on activities does not necessarily mean that learners will be able to make sense of the materials for themselves and that manipulation of materials alone may not provide sufficient feedback. Analysis showed that although children explored more in free sessions, this did not lead to higher levels of discovery. Guided exploration produced more episodes of discovery.

As discussed throughout this thesis, the tangible paradigm introduces novel possibilities for implementing scaffolding and providing feedback. The dyad 'extrinsic feedback / action as communication' was predominant in guided sessions, with strong statistical significance. This is an expected result as extrinsic feedback was part of coaching, and action as communication was a strategy children used for attending to the facilitators' requests and posed challenges. The top contributors for exploration in Figures 9.3 and 9.4, indicate the triad 'action as exploration / informational feedback / action as revision' was the most successful combination for supporting discovery, associated with the appeal of the physical elements of the system. This suggests that intrinsic feedback, when given through meaningful representations, was successful for making children perceive the system's response for their actions, engendering follow-up actions. Informational feedback was also found to occur more frequently in episodes of discovery in guided sessions, which reinforces the idea that some guidance is beneficial to provide a minimal underlying structure for productive exploration, and is consistent with previous findings that participating in guided discovery is more beneficial for learners than being provided with an explicit explanation (Alfieri et al., 2011).

The importance of intrinsic feedback was reinforced by the finding that non-informational feedback was the greatest cause of disruption in both guided and free sessions. Disruption was more frequent in free sessions - which is somehow expected, as children were interacting in a less controlled environment. Thus, external guidance was effective in easing disruption, which is reinforced by the identified predominance of engagement with technology, technical constraints and confusion from perceived affordances as causes of disruption in free sessions, when compared to guided. This indicates that coaching was key for keeping children's attention away from the technical aspects, and for avoiding incurring in technical limitations and misuses of the physical devices due to culturally constructed interpretations that were not part of the designed scenarios. It also shows the difficulty of embedding in the design of the tangibles constraints to guide interaction through 'happy paths' free of technical interference, and the importance of facilitation to compensate for this.

Analysis showed that, added up, episodes of discovery were much more frequent than episodes of disruption, which indicates that overall, the result of the discovery learning activities with tangibles and children with intellectual disabilities was positive. This constitutes an important finding as, despite the popularity of the approach of interaction with concrete materials in special education, specific evidence of its effectiveness, going beyond physical engagement, remains unclear. Analysis also showed the key value of providing informational feedback to exploratory actions, and the importance of minimal guidance from an educator to establish an environment more prone to discovery. The ideal format of external guidance in combination with tangibles' intrinsic feedback must be further investigated.

Chapter 10 – Conclusions

This thesis aimed to investigate how and which characteristics of tangible interaction may help children with intellectual disabilities productively engage in processes of discovery learning. Hands-on approaches are highly recommended for children who are intellectually disabled, because they benefit from the interaction with physical artefacts. However, the lack of structure of exploratory activities and the limitations of the artefacts in terms of feedback and scaffolding introduce important barriers for these children's learning and impose great demands for teachers' assistance. The first part of this thesis laid out the arguments in favour of tangible technologies as novel artefacts whose characteristics suggest a great potential for addressing these problems. The investigative empirical research undertaken provided evidence for some of these potentialities, but also revealed unanticipated challenges to interaction and learning introduced by the tangible paradigm, in the context of intellectual disabilities. The main contributions that resulted from this research are presented in this concluding chapter.

Contributions of the thesis

Contributions to the theoretical field

As discussed in Chapter 4, education is a popular domain in research in tangible interaction and a few theoretical frameworks have taken different perspectives to analyse tangible interaction for learning. Generally, potential advantages of tangibles for the learning process include: physical engagement with concrete materials to explore concepts through multiple senses; bridging gaps in mappings between concrete and symbolic representations; creating collaborative exploratory environments; and increasing accessibility. However, empirical evidence to support such claims is still incipient, particularly in the case of children with intellectual disabilities. It is rather consensual that providing physical materials, engaging multiple senses and lowering the barrier of accessibility seem like good ways forward, but the if and how of whether they actually help children with intellectual disabilities learn remain unclear. This thesis contributes to the theoretical field of tangibles for intellectual disabilities through empirical evidence and theoretical reflections on some key themes of exploratory tangible interaction.

On the multimodality of representations

One of the key characteristics of tangible technologies is the combination of different modalities of representations, thus engaging multiple senses in interaction. However, little is known about the specific role of each modality of representation. To date, the only theoretical framework on tangibles for learning that marginally approached the subject was Price et al. (2008). This thesis extends Price's initial discussion by examining the effects of modalities of representations (physical and digital, where the latter comprises textual, auditory and visual) for children with intellectual disabilities.

Firstly, the alleged importance of physical representations for children who are intellectually disabled was confirmed in this research by students' spontaneous engagement in exploring spatial configurations of physical objects, and by their interest in properties like shape, colour and texture. Physical characteristics also appeared in the quantitative analysis as one of the main contributing aspects for enabling episodes of exploration that led to discovery. However, children in some cases disregarded the digital feedback to their actions in favour of a sole focus on the physical, as if playing with traditional manipulatives or assembly kits. Such exploration of physical objects regardless of their associated digital representations revealed that the importance of physicality for children with intellectual disabilities can be so high as to make digital feedback go unnoticed. In tangible systems, ignorance of the digital feedback means key educational goals are not being communicated to the child, which suggests that in these cases tangibles failed to fulfil their alleged benefit of establishing physical-digital mappings that facilitate comprehension of abstract concepts. The great challenge lies in combining the different modalities of representations within the hybrid physical-digital context in a meaningful way for the children, making the physical-digital couplings tight enough to avoid situations where children interpret different modalities of representations in isolation.

In this sense, among the three types of digital representations of the tangibles analysed - textual, auditory, and visual (i.e. graphical / pictorial) - visual was found to be by far the most adequate form of representation for providing meaningful feedback. It naturally attracted students' attention, leading to engagement in exploration and being the most productive form of digital representation for conveying concepts. Nevertheless, the risk of a prevailing representation in a multimodal context also applies here - visuals can be attractive to the point of diverting children from other - equally important - representations of the system. This highlights the hidden challenges (especially for users with intellectual disabilities) brought about by multiple representations and modalities, which are commonly cited as alleged benefits of tangible systems.

Auditory representations were less easily perceived, and even when they were, students did not naturally understand the sounds as feedback for their actions. In other words, in many cases sounds did not represent relevant stimuli for the students and thus were not brought to their attention nor interpreted as meaningful elements of the interaction. However, an important point needs to be made here as the audio systems employed proved to have inappropriate design characteristics for dealing with intellectual disabilities, in particular delayed feedback and non-embodied audio, but also excessively abstract associated visual representations with no clear conceptual meaning. Therefore, conclusions on the auditory modality must be contextualised within these limitations, i.e. findings only hold for systems implemented through delayed feedback and distant coupling, and further investigation is needed with audio systems that present more suitable characteristics for perception and mappings.

Finally, texts presented a barrier for most students, as many were illiterate. Still, combining texts with other forms of representation may stimulate children to overcome their difficulties with reading.

On concrete-abstract links

Tangibles are expected to provide physical-digital mappings that support the problematic process of linking physical artefacts with their symbolic representations and associated abstract concepts. At the core of this process is the relationship between actions taken by the child with the interaction devices and the consequent effects in the system, which should trigger reflection based on the mappings between representations. The literature discusses a number of aspects that play a role in this process of discovery, and this research has found that some key design choices can facilitate perception of these mappings by students who are intellectually disabled.

Firstly, deeply related to modalities of representations discussed in the previous section, is the spatial coupling between physical representations and digital information, which has been extensively discussed in several frameworks. Besides the influence of the modality itself, the properties of the links between physical and digital representations also influence the extent to which they are perceived as a same entity or separately. The empirical studies showed that physical and digital representations should be spatially contiguous (as in the tabletop) or coincident (as in the augmented object) to improve the perception of action-effect relationships, and consequently, the construction of links between concrete and abstract. The more 'distant' in space the types of representations are (such as audio played from a computer in the corner of the room, or visuals projected on a wall), the harder for the children to establish representational mappings.

Another crucial aspect for children's comprehension of action-effect mappings is temporal contiguity. This research has shown that, for children with intellectual disabilities, system feedback should be immediately subsequent to the child's action. Delayed feedback as a design choice, such as in the case of the drum machine and the Loop Loop application, is not adequate for children with intellectual disabilities, as they are not able to link their actions to feedback that is not immediately subsequent.

A third important design choice to be made is for simple causality, meaning that system effects solely depend on the specific action of the child, and not on other variables of the environment. This helps to make the link between cause and effect clear enough for the child with intellectual disabilities to grasp.

Last but not least, an aspect that may seem obvious but should not be taken for granted is that feedback must be provided through explicit representations. This finding arose from design choices that consisted in embedding meaning in the absence or interruption of effects (implicit forms of representations). For example, in the tabletop environment, absorption was illustrated by interrupting the light beam. Children's general perception of this was that 'nothing was happening', and they tended to move on to other explorations without assimilating or thinking about the concept of absorption. This means that the absence of effects as feedback for action is not perceived by children with intellectual disabilities as meaningful, but rather as a fact to be ignored.

This type of non-informational feedback was the greatest cause of disruption in exploratory interaction, while informational feedback was the most important contributor for discovery. To sum up, three conditions for abstraction from tangibles in the context of intellectual disabilities can be derived: (i) physical and digital representations should be contiguous in time and space; (ii) causality of effects should solely depend on the child's action; and (iii) feedback should be provided through explicit representations. It is important to note, however, that although these design choices facilitate the perception of links between concrete and abstract representations, it does not follow that children with intellectual disabilities then reach abstract generalisations on the conceptual domain.

<u>On conceptualisations and perceived affordances</u>

Besides building associations between representations, another key aspect for supporting discovery learning relates to children's conceptual interpretations of the elements of a tangible environment. In tangible systems, the physical components have associated meanings relevant to the domain, and their physical affordances are expected to enable natural and intuitive interaction situated within realistic simulations that capitalise on people's familiarity with the physical world. Several frameworks attempt to organise and classify relationships between physical objects and their conceptual meanings (e.g. objects as controls of digital information and objects that resemble the information they represent). More specifically, frameworks on tangibles for learning analyse how the physical properties of objects map to learning concepts, if at all.

The present research reinforced indications in the literature that, for students with intellectual disabilities, it is essential to provide connections with familiar contexts through the systems' representations, particularly by taking advantage of physical properties of the objects. Systems like the interactive tabletop, where the interaction objects have a role in the simulation that is similar to their role in the physical world, were much more successful in engaging children in discovery learning than systems like the drum machine, where the physical form of the objects did not hold any metaphorical correspondence to the conceptual object. Nevertheless, these strong metaphorical links still did not guarantee students' comprehension of underlying concepts. Tangible exploratory interaction, as undertaken in the empirical studies, was not sufficient to significantly improve students' capability of abstraction and generalisation. Even when they understood the rules illustrated by the behaviour of the objects, they made very few associations with the physical world, but mostly gave technical and pragmatic descriptions of what they observed. Conceptual discoveries were much less frequent than discoveries that corresponded to literal comprehension of the functioning of the simulation, which is expected, as (i) the move from empirical to formal knowledge is a hard process not only for children with intellectual disabilities; (ii) time spent with the materials was short to reach maturation of concepts; and (iii) conceptual discoveries were measured simply in terms of frequencies of types of utterance.

Another aspect that hindered the process of conceptualisation referred to perceived physical affordances. Realistic simulations and the use of 'real' objects can introduce expectations that are not necessarily met by the system design, and meaning attached to artefacts by designers is not necessarily transparent to students or interpreted by them as the designer anticipated. This research revealed that some perceived affordances of physical elements of the systems, although 'natural' and 'intuitive' from a cultural perspective, in the context of discovery learning became counterproductive, for deviating students from the core concepts that the scenarios aimed to convey. For instance, students attempted to remove the lid of the augmented object's container and to turn the torch from the tabletop system on and off, or engaged in repetitive actions like pressing the Sifteo cubes in situations where this was not part of the repertoire of designed actions. This highlights the importance of acknowledging culturally constructed affordances that go beyond the constraints of system design. This is particularly important when designing for students with intellectual disabilities, because it is harder to prevent these children from engaging in disruptive or unpredicted actions, as they may not understand explanations or comply with instructions. The quantitative analysis pointed to confusion from perceived affordances, technical aspects and engagement with technology as significant causes of disruption in exploration. Therefore, ideally, efforts should be made to avoid affordances that invite actions with no meaningful results, although this is fairly hard to achieve when making use of authentic objects.

On the role of actions

Bodily activity in tangible interaction for learning is considered to be at the basis of thinking and reflection, as knowledge is believed to come from associations between actions performed on objects and the resultant representations, rather than from the properties of objects alone. There is a belief that kinaesthetic experience enhances perception and thinking, and physical activity helps to make abstract concepts more accessible. This research identified three main roles for actions within processes of discovery learning, for children with intellectual disabilities: imitation, communication and exploration.

Children with intellectual disabilities are generally reluctant to use their own judgement and take initiative, as a sign of low self-concept and a strategy to avoid failure. As a consequence, they tend to rely on external cues and on behaviours of others, often imitating the actions of others. It is thus a good idea to design systems where imitation can be productive, i.e. by engaging in the same actions as a peer or teacher, the child will have the chance of perceiving concepts and making conclusions that were not apparent through pure observation of the very same action. This may not be as straightforward as it seems. In the case of the drum machine, when the child imitated the researcher’s action of placing a block in a specific region of the interactive area did not engender reflection, because the decision of where to place a block is the core concept of the application, as it is what determines the sound to be played. Following someone else's action in this case merely constituted a safe way for the child to interact with the system. Differently, imitation with the augmented object helped students reflect about the nuances of the object's behaviour as they performed themselves the actions they had only seen their peer do. This shows that to capitalise on imitation, comprehension should be linked to the act of *performing* and *observing* the consequences, so that imitation becomes educationally relevant. Another issue to keep in mind is that in the case of students with intellectual disabilities, imitating a peer may take both children towards an undesired path, if the imitated action is disruptive or counterproductive. In this case, interference from the educator may have a key role.

Actions also served as forms of communication. As indicated in the literature, for the students with intellectual disabilities, acting is easier that speaking. When asked direct questions, students showed signs of being nervous and fear of giving wrong answers, besides the fact that many of them had difficulties to express their ideas verbally. Actions were thus a form of giving answers, explanations and demonstrations. Indeed, concrete representations are easier to talk about, describe and analyse, than language-based solutions: it is easier to describe physical actions on physical objects than to describe operations on symbols. Although most of the time students could not verbally articulate general rules about the behaviour of the tangibles, they showed they had grasped the rules by performing coherent actions to answer questions or give explanations. Therefore, artefacts should be designed to allow students to express their ideas, being alternative ways of communication so that interaction with the system and with other persons through the system is not hindered due to communication problems. Action as communication was much more frequent in guided sessions, when children were constantly solicited to interact with the facilitator.

Finally, exploration was the most important role of actions in the context studied, being a fundamental aspect of discovery learning. An important aspect that the research highlighted was the need for a low barrier for initiating exploration. This can be obtained by capitalising on familiar representations and making opportunities for action clear through physical affordances, which worked very well with the tangible tabletop, whose coloured blocks and torches naturally invited children to touching and manipulating. An opposite situation occurred with the drum machine, where actions were not clear and students were unsure what to do, probably due to high level of abstractness and low intuitiveness of the action of placing blocks on a piece of paper. Inviting exploration is particularly relevant for children with intellectual disabilities, who resist taking initiatives, and for whom the fear of making mistakes is higher. Decreasing the fear of mistakes and the pressure for 'doing the right thing' can also be achieved by suggesting exploratory activities instead of specific tasks to be completed, and designing actions that do not have a 'permanent effect', but can be undone and redone and not necessarily imply a definite answer or decision. Action as exploration was one of the main contributors for discovery.

On the level of guidance

It is known in the literature that students with intellectual disabilities have problems with experimentation consisting of poorly structured activities, and teachers are advised to coach students through the reasoning process, directing their thinking, and not leave them to discover concepts on their own with a set of materials. On the other hand, tangible technologies have the potential of providing more adequate feedback and scaffolding and reducing the demands on the teacher.

Free and guided sessions with the tangible tabletop were run to analyse the effectiveness of the system's feedback and the need for external facilitation. Informational feedback provided by the tangible tabletop proved to be crucial for encouraging children's exploration, being more effective than extrinsic feedback given by the facilitator. Extrinsic feedback was not effective in overcoming instances of non-informational intrinsic feedback, which was the greatest cause of disruption in both guided and free sessions. Guided sessions also failed in inducing more episodes of conceptual discoveries in relation to free sessions, but they facilitated literal comprehension more than free sessions, which can be considered a step towards conceptual learning. Facilitation was also beneficial for keeping children's attention away from technical aspects, and for avoiding problems related to technical limitations and misuses of the physical devices due to perceived affordances. Guided sessions did obtain lower levels of disruption.

In summary, although guided sessions did not represent a statistically significant difference for children's conceptual comprehension, overall it was found to be beneficial to provide a minimal underlying structure for productive exploration. Nevertheless, questions on how best to provide adequate guidance for children with intellectual disabilities in guided discovery learning remain open, specifically concerning the type of the facilitation given and the design features of the tangibles.

Implications for designers

The qualitative analysis presented in Chapter 8 produced twelve guidelines for the design of tangibles to support children with intellectual disabilities in exploratory processes. Although analysis was structured in four broad themes (types of digital representations, physical affordances, representational mappings and conceptual metaphors), the guidelines that emerged throughout the process are grouped here into categories that convey a better structure to guide designers. These guidelines are an important contribution of the thesis, and aim to help educational designers to make choices that lead to developing artefacts that are more adequate for supporting children with intellectual disabilities, particularly in processes of discovery learning.

<u>Digital and physical representations</u>

Guideline D1: Text should be reduced, and combined with other ways of conveying the same information that do not depend on literacy skills, such as pictorial representations.

Guideline D2: Auditory representations must be sufficiently loud, clear and simple, and should not constitute the main or sole form of conveying meaning when action-representation mappings and coupling of representations are not direct.

Guideline D3: For easily attracting attention, visual representations are recommended as a way of engaging students in interaction, but should be discreet if they are not the main type of representation in the system.

Guideline D6: Design should take into account that children perceive physical representations more easily than digital.

Actions

Guideline D4: Actions invited by physical affordances should lead to useful and consistent effects.

Guideline D5: Informational feedback should be provided to discourage actions that although invited by physical properties of objects, are ineffective in the system.

Guideline D7: To encourage exploration through action, tangibles should capitalise on transient representations (i.e. that can be undone and redone), and avoid right/ wrong approaches.

Action-effect mappings

Guideline D8: Digital feedback should preferably be represented through production of effects, rather than absence of effects or interruption of current events.

Guideline D9: Action-effect mappings should be contiguous in time: immediately subsequent feedback should be provided for user actions.

Guideline D10: In action-effects mappings, preference should be given to simple causality based on student's actions.

Guideline D11: Input and output events should be contiguous or coincident in space to increase comprehension of action-effect mappings.

Conceptual metaphors

Guideline D12: Representations should make metaphorical references to the conceptual domain, building on objects' physical properties and evoking links with the physical world.

Implications for educators

The idea that learning disabilities can be consequences of children's unresponsiveness to the generally effective instructional setting (Vaughn and Fuchs, 2003) has direct impact on policies for inclusive education. Including a child with special needs means not only educating them in a mainstream school, but also integrating them in the curriculum and helping them achieve and participate fully in school life (DfEE, 1997; DfES, 2004; Mittler, 2000). However, the presence of students with learning difficulties is challenging in terms of planning provision and developing staff expertise (AuditCommission, 2002). A recommended approach to help effective inclusion is to provide adequate learning materials or special equipment within group activities (DfES, 2001). Field research presented in Chapter 6 pointed to the need for more educational resources that are adequate and accessible for children with learning difficulties, to help them understand, communicate and express themselves, and interact with others. The solutions examined in this research were not specially designed for children with intellectual disabilities - rather, they are tools that can be used by all, in mainstream contexts. In other words, they can be seen as means of addressing individual difficulties in a manner that can be incorporated into the ongoing general instructional environment, facilitating policies of inclusion (Vaughn and Fuchs, 2003). The detailed analysis of the use of such tools by children with learning difficulties, presented in this work, can give insights to educators as to how to broaden these children's participation in classroom activities, helping to improve the quality of the learning experience of all students. Quantitative analysis (Chapter 9) also reinforced the importance of facilitation to support discovery in tangible environments, and the challenges involved in balancing extrinsic and intrinsic feedback. Four guidelines emerged from the analysis, which indicate good practices for conducting activities with tangible technologies and children with intellectual disabilities. The guidelines are presented below, numbered according their order of appearance throughout the analysis.

Guideline F1: To foster learning through intentional affordances and imitation, the intellectually disabled child should preferably work with a more able person.

Guideline F2: When facilitating interaction, educators should recognise the learners' actions as part of the communication process and favour questions that can be answered through actions.

Guideline F3: For productive discovery learning with tangibles, educators should provide extrinsic feedback when students are unable to make sense of the intrinsic feedback produced by the systems.

Guideline F4: When simultaneous actions and/or digital effects occur in interaction, the educator should facilitate the learner's perception of causality by isolating action-effect couplings.

Limitations of the research

From a philosophical perspective, in spite of following a socio-constructionist approach, this research focused on students' interaction with tangible technologies, leaving out variables related to the environment where such interaction is expected to happen, i.e. the classroom context and routine. In other words, empirical studies ran in artificial contexts like a university lab cannot account for what may happen if teachers decide to run a similar activity in their classes, and how the factors from school environments can modify the interaction and the activity. Although this limitation is acknowledged, it was a conscious choice justified by time and scope of the research. A decision had to be made as to which aspects of the complex interactions that take place during learning processes were to be analysed in detail. Despite the limited scope, the thesis is not 'technologically determinist', for it did not aim to evaluate the efficacy of particular hardware or software per se, but rather to analyse which aspects of a new paradigm of technology could be particularly beneficial for children with intellectual disabilities in discovery learning activities.

Empirical studies consisted of short sessions, which may not account for post-novelty effects, or for interactional and cognitive development of students through prolonged use of the artefacts, including how they adopt and adapt them. Again, time and scope limitations and practical reasons related to school involvement and infrastructure for setting up the prototypes of tangibles made longitudinal studies prohibitive. Although answers cannot be given to matters related to learning over long periods like a school year for example, the short sessions undertaken followed a scientific research methodology, and provided data that allowed a rich analysis of a number of aspects of tangible interaction, providing explanations that will help the community to understand similar cases.

An issue that also relates to cognitive development and short sessions is how to assess children's conceptual comprehension. This is particularly challenging as children with intellectual disabilities have difficulties in verbalising their thoughts and ideas. While comprehension of how the system works and how to interact with it could be identified through children's actions, conceptual comprehension was mostly coded based on evidences in speech, as it was very hard to perceive it otherwise. A method for such evaluation is needed, which may include post-sessions activities with the goal of verifying which concepts children learned.

Another limitation refers to the facilitation of empirical sessions. Most sessions were facilitated by the author of this thesis. However, groups reacted differently to coaching in structured sessions, and this led to variation of the level of guidance throughout a single session. There were moments in guided sessions when exploration escaped the researcher's control as students got engaged to the point of making their own decisions and taking the initiative. This is, per se, an interesting indication of the potential of tangibles for discovery learning, but it may have introduced some bias in the data for the comparative analysis of free versus guided sessions. This difficulty with facilitation is not simple to solve, as it constitutes a complex process of interaction with humans where it may not always be possible to follow a rigid script. Flexibility is inherent to the facilitation of discovery learning activities, particularly with children with intellectual disabilities, who may not always understand or comply with instructions. However, an important lesson learned is that if a goal exists to compare conditions that directly involve the method of facilitation, efforts should be made to be as systematic as possible when running the activities. Four groups that participated in the tabletop sessions were coached by their teachers, who felt the need to give specific guidance for their students because they were interacting with such unfamiliar artefacts. Despite the researcher's instructions on how to mediate children's interaction in the context of the research, each teacher's facilitation consisted of very close guidance that limited children's exploration excessively. Teachers seemed to be striving to push their students to produce 'useful' data for the researcher, and appeared frustrated as they judged the sessions unproductive due to students' difficulties. Such differences in facilitation led to the exclusion of the data from the teacher-facilitated sessions from the quantitative analysis.

Future research directions

Finding the optimal balance in discovery learning between external guidance and intrinsic feedback provided by tangibles is probably the greatest challenge left unanswered by this research. Future studies should address this issue by specifically focusing on type and amount of external facilitation versus system feedback. This could be done with the help of educators to determine the types of facilitation that could be tried, in conjunction with system developers and interaction designers to level the amount and type of feedback given and the appropriate situations for such. A number of combinations between methods of facilitating and feedback given could be investigated.

The amount of data generated by the empirical studies has the potential to answer many questions beyond the ones made by this research. A choice was made here to look at the overall picture to capture as many different aspects of tangible interaction as there appeared to be. If on one hand this produced a holistic qualitative analysis, on the other hand it made deep, detailed analysis of each aspect prohibitively time-consuming, opening up opportunities for future work on the same data corpus. Open questions include: which aspects of tangible interaction contributed most for each type of cognitive outcome? and what was the distribution of types of cognitive outcomes across time, i.e. was there a trend from mostly discovering how the system works, to literal comprehension of the system, then to reach conceptual comprehension?

An interesting comparative study could be performed with data obtained in previous empirical studies with the tangible tabletop where the author was also involved, and which adopted a very similar research methodology, but with typically developing children (Pontual Falcão and Price, 2011; Price and Pontual

Falcão, 2011). This study would be interesting for the context of inclusion, as it could pinpoint specific differences and similarities between the groups to help teachers in using this type of technology in heterogeneous classes. Specific questions here could be (i) what is the expected ratio of discoveries of types 1, 2 and 3 in a discovery learning context for typically developed children? and (ii) are there significant differences in the ratios and how they change over time for the two groups? This could indicate the relevance of the design guidelines to all learners and guide universal design of tangibles for learning, i.e. developing artefacts that would be adequate for all users.

Another aspect to be analysed is peer collaboration. Tangibles create opportunities for collaborative interaction, but children with intellectual disabilities have difficulties in collaborating with peers, so an interesting research question would be how tangibles can encourage their collaboration. Although the studies were not designed with a focus on collaboration, they were run in groups, so data available can be a starting point for investigating this issue and planning future studies.

From a broader perspective, a future research direction consists of setting up longitudinal studies in schools, where tangible technologies would be integrated to lessons throughout the school year. This could be implemented through a research project that extends the studies presented in this thesis and uses the findings as starting points and data corpus to inform future studies. The data of teacher-facilitated sessions with the tangible tabletop produced in this thesis could serve this purpose, as it could anticipate difficulties that the teachers may face in using this type of technologies with intellectually disabled students. The length of sessions, for example, was found to be short for children's maturation of concepts, but adjusted to children's attention span. This could be used as a reference to find the optimal combination between length of sessions and repetition of sessions on the same topic. In addition, the tangible technologies to be used could be designed or adapted according to the guidelines of this thesis, but also considering school syllabus, therefore being really useful for teachers and students in the school context. Such a research project implies intensive joint work between researchers and teachers. Detailed joint planning must be performed to ensure that activities undertaken meet learning goals as well as research aims, being suitable for schools but also being in line with scientific methodology. To reach this goal, the methodology of teacher facilitation during the activities with tangibles would have to be previously determined with full agreement of both sides.

The motivation of this thesis, above all, was to point to paths that can improve the life of children with intellectual disabilities, by making contents more accessible to them, opening up new opportunities for learning, and improving their self-confidence and self-esteem. Kirk and Gallagher's quote from 1979 still holds when they say that "we have been traditionally too pessimistic about exceptional children and consequently find ourselves continually being surprised at what they can do if we are imaginative enough to find better methods and procedures by which to stimulate them" (1979, p. 7). A little step taken in this direction with the contribution of this thesis will constitute the greatest successful output there could be.

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Appendices

Appendix 1 - Ethics

This research adhered to the BERA Professional Ethics Code, and was approved by the Research Ethics Committee of the Institute of Education before any kind of data collection was performed. In addition, the researcher underwent a Criminal Record Bureau check, as the research involved children.

Information letters and leaflets distributed to schools and parents describing the research, and consent forms giving the researcher authorisation to undertaken the field research in schools and having the participation of the children in the empirical sessions are presented in the following pages.

When the ethics forms were prepared, the research had a different title, and the aims were stated in slightly different terms from what is presented in the final version of the thesis. However, the research techniques (interviews, observations and empirical sessions) remained the same, as well as the overall goal of the research. Changes throughout the process reflect the flexibility and serendipity inherent to qualitative research. The ethics forms are presented here in the way they were originally produced and distributed.

Information letter for schools

Schools administrators and teachers received an information letter plus an oral explanation given personally by the researcher about the research topic, aims and procedures. The information letter served as an official document for the schools records, and as a written document that could be distributed among teachers to inform them of the research.

IOE LONDON

Leading education and social research
Institute of Education
University of London

School letter

PhD research:
The role of tangible technologies in promoting special education inclusion

PhD candidate:
Taciana Pontual Falcão (t.pontual@ioe.ac.uk)

Dear Sir / Madam:

I am a PhD student at the Institute of Education, University of London. I am undertaking my research under the supervision of Dr. Sara Price and Prof. Diana Laurillard, to investigate how tangible technologies may help children with special educational needs to collaborate and learn. Technological devices have proved, in recent years, to be valuable resources for education. The term "tangible technologies" refers to systems in which physical objects are integrated with technological devices. This integration provides both the advantages of the concrete and the interactivity and dynamics of technology. The multisensory aspect of tangibles makes them especially suitable for children with special needs. In addition, tangible environments are naturally collaborative, which may improve the participation of pupils with special educational needs and their interaction with peers.

This research will involve pupils in the last year of primary school and early years of secondary school, and I wondered whether you would be interested and willing for your school to participate. The research would consist of two main phases:

1. Observing classes and interviewing the teachers. The aim of this phase would be to understand better the main issues teachers face when teaching children with learning disabilities and to identify some common characteristics among those pupils, to envisage how technology could be used as a valuable resource. The amount of hours of observation would depend on the school availability, but one suggestion would be one school day.
2. Undertaking 30 minutes sessions with groups of two or three children exploring a tangible environment (interactive tabletop – see pictures on the next page) at the London Knowledge Lab (Institute of Education), with the aim of evaluating the impact of such technologies on children's collaboration and knowledge construction.

If you would be willing for your school to take part, I would be very pleased to come and discuss the project with you further. You may also choose to participate in one of the phases only. Please feel free to contact me by telephone or e-mail if you wish. I look forward to hearing from you.

Yours sincerely,

Taciana Pontual (tel: 020 7763 2199; email: t.pontual@ioe.ac.uk)

Consent form for schools

Having been given the information letter, head teachers were asked to sign consent forms authorising the researcher to observe classes in the school and interview teachers who were willing to take part.

Leading education and social research
Institute of Education
University of London

School Consent

PhD research:
The role of tangible technologies in promoting special education inclusion

PhD candidate:
Taciana Pontual Falcão (tpontualdarochafalcao@ioe.ac.uk)

I agree for the researcher Taciana Pontual Falcão to observe classes in the school and interview teachers (if they wish to take part), as part of her PhD research.

School name __________________________

Head teacher's name __________________________

Signed __________________________ Date _______________

Consent form for teachers

Teachers who agreed to be interviewed were asked to sign consent forms authorising the information from their interviews to be used in the research.

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Institute of Education
University of London

Consent form

PhD research:
The role of tangible technologies for special education

PhD candidate:
Taciana Pontual Falcão (tpontualdarochafalcao@ioe.ac.uk)

I agree for the researcher Taciana Pontual Falcão to anonymously use the information given in this interview as part of her PhD research.

Name: ___________________________________

Signed: ___________________________________

Date: _______________

Information leaflets for parents

Schools that agreed to take part in the research received leaflets to be distributed to parents. The leaflets explained in colloquial language key information about the research, and asked for parents' contribution by talking to their children about it, obtaining their agreement to take part, and authorising them to do so.

Leading education and social research
Institute of Education
University of London

London Knowledge Lab
Institute of Education

The role of tangible technologies in promoting special education inclusion

Information for parents
Please will you help with our research?
This leaflet provides information about our research, and we would be pleased to answer any further questions you might have.

This PhD research project from the Institute of Education, performed by Taciana Pontual under the supervision of Dr. Sara Price and co-supervision of Prof. Diana Laurillard, aims to investigate how tangible interfaces may help including children with special educational needs in mainstream schools. Since the Warnock Report in 1978, there has been a growing tendency for inclusion. However, the process of inclusion is not only about placing SEN children in regular classrooms, but also providing them with effective learning opportunities and suitable learning challenges.
Technological devices have proved, in recent years, to be valuable resources for education. The term "tangible technologies" refers to systems in which physical objects are integrated with technological devices. This integration provides both the advantages of the concrete and the interactivity and dynamics of technology. The multisensory aspect of tangibles makes them especially suitable for children with special needs.

Who will be involved in the research?
The project will involve pupils in early years of secondary school, with and without special educational needs, from different mainstream schools. The Head of the school has already agreed for this research to take part in your child's school.

What will happen to you if you and your child agree to take part?
If you agree, your child will have the opportunity to 'play' with the tangible environment together with two classmates, in one session of about 30 minutes. The researcher may ask them to talk about what they are doing during their 'play'. The sessions will be video-recorded, as it is difficult for researchers to see everything that happens during the sessions. We are not looking for right or wrong answers from the children, but for how the tangible environment might help them collaborating and building knowledge together. I hope your child will enjoy playing in the tangible environment and talking to the researcher. Please would you explain the research to your child and see if they would like to take part. We will also ask the children during sessions and make it clear that they can drop out at any time if they wish.

Does your child risk being distressed for having learning difficulties?
Children with and without special needs will be working together in the same activity. Children with special needs will be given extra attention and help if necessary, but there won't be right and wrong answers and their learning difficulties will not be put in evidence whatsoever during the research.

Will doing the research help you?

The research will mainly collect information about how tangible technologies can help promoting the effective inclusion of children with special needs. By agreeing for your child to take part, you will be contributing to promoting effective inclusion in schools in the future.

Who will know that you have been in the research?
Only the researcher and supervisors will know the children who take part. We will not tell anyone outside the research the individual names or personal details of anyone taking part. We will not use images or video footage of your child for academic presentations or publications or project web pages without your specific consent (see consent form). We will keep videotapes, images and notes in a safe place, and will change all the names in our reports, publications and presentations.

Do you have to take part?
You or your child decide if you want to take part and, even if you say 'yes' now, you can drop out at any time or say that you don't want to answer some questions.
Please can you let us know if your child can take part by signing the consent form.

Will you know about the research results?
Your child's school will be sent an electronic version of the PhD thesis at the end of the research by 2014.
The project has been reviewed by the Faculty Research Ethics Committee, [??].

Thank you for reading this leaflet.

For further information please feel free to contact Taciana Pontual, e-mail: tpontualdarochafalcao@ioe.ac.uk; tel: 020 7763 2199.

Consent form for parents

Parents who read the information leaflets and agreed for their children to participate, with their own consent as well, were asked to give formal written consent.

IOE LONDON

Leading education and social research
Institute of Education
University of London

Consent form

PhD research:
The role of tangible technologies in promoting special education inclusion

PhD candidate:
Taciana Pontual Falcão (tpontualdarochafalcao@ioe.ac.uk)

I have read the information leaflet about the research. ☐ (please tick)

I am happy for my child to participate in the research. ☐ (please tick)

I give consent for images/video of my child to be used in (please tick any that apply):

Written publications ☐ (please tick)

Conference presentations ☐ (please tick)

Webpages ☐ (please tick)

I give consent for the researcher to have access to my child's statement of special educational needs *(if applicable)* ☐ (please tick)

Child's name __________________________

Parent/guardian name __________________________

Signed __________________________ Date ________________

e-mail contact __________________________

or

Telephone contact __________________________

Thank you!