RAFIGH: A LIVING MEDIA SYSTEM FOR MOTIVATING TARGET APPLICATION USE FOR CHILDREN

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ABSTRACT

Digital living media systems combine living media such as plants, animals and fungi with computational components. In this dissertation, I respond to the question of how can digital living media systems better motivate children to use target applications (i.e., learning and/or therapeutic applications)? To address this question, I employed a participatory design approach where I incorporated input from children, parents, speech language pathologists and teachers into the design of a new system. *Rafigh* is a digital embedded system that uses the growth of a living mushrooms colony to provide positive reinforcements to children when they conduct target activities. The growth of the mushrooms is affected by the amount of water administered to them, which in turn corresponds to the time children spend on target applications.

I used an iterative design process to develop and evaluate three Rafigh prototypes. The evaluations showed that the system must be robust, customizable, and should include compelling engagement mechanisms to keep the children interested. I evaluated Rafigh using two case studies conducted in participants' homes. In each case study, two siblings and their parent interacted

with Rafigh over two weeks and the parents identified a series of target applications that Rafigh should motivate the children to use. The study showed that *Rafigh* motivated the children to spend significantly more time on target applications during the intervention phase and that it successfully engaged one out of two child participants in each case study who showed signs of responsibility, empathy and curiosity towards the living media. The study showed that the majority of participants described the relationship between using target applications and mushrooms' growth correctly. Further, *Rafigh* encouraged more communication and collaboration between the participants. *Rafigh's* slow responsivity did not impact the engagement of one out of two child participants in each case study and might even have contributed to their investment in the project. Finally, *Rafigh's* presence as an ambient physical object allowed users to interact with it freely and as part of their home environment.

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Table of Contents

List of Tables

LIST OF FIGURES

Chapter 1
Introduction

Digital interactive systems hold great potential for motivating children to conduct positive activities that support learning, communication and behavior change. Children are fascinated by interactive digital computer activities and games. In recent years, thousands of digital games and other computer-based applications or apps have emerged that aim to incorporate learning and therapeutic elements into their design (Corbett, 2010; McGonigal, 2011). For children with disabilities, these digital systems can provide valuable opportunities to practice language, communication and social skills, among others (Bernardini et al., 2014; Bälter et al., 2005).

In this dissertation, I examine how digital systems can help motivate children use targeted applications that support therapeutic and learning outcomes in the home context. Here, I use the terms *targeted applications* or *target apps* to refer to computer applications that benefit children by supporting therapeutic and/or learning outcomes. *Rafigh* is an embedded digital system that uses a living media interface to provide positive reinforcements when children conduct targeted activities. It consists of a living mushroom colony connected to an irrigation system that is controlled remotely. The amount of water administered to the mushrooms is a major determinant of the colony's growth and is used to positively reinforce children's engagement in target activities. *Rafigh* is designed for use in the home context and is intended to encourage empathy and responsibility in order to engage and motivate children to use target applications that are designed to bring about learning and/or therapeutic outcomes.

I chose the term "*Rafigh*" as an identifier for the system. In Persian and Arabic, *Rafigh* (Persian: رفیق, ræfık) means "companion", a meaning that I decided captured the intended role of the system as an interaction partner for the children. As I will describe in chapter 5, the system was developed using an iterative prototyping process, during which it underwent different changes; I will use *Rafigh* as an umbrella term to refer to the system in all such iterations.

I adopted the *Research through Design* (RtD) methodology as the framing methodology for this project. RtD is a well-known methodology in the research domain of Human-Computer Interaction and will structure this research project around reflection and the iterative refinement and synthesis of findings. This methodology supports experiential inquiry and stakeholder participation and is particularly suitable for explorative research in new research areas (Zimmerman et al., 2007; Frayling, 1993; Fallman, 2007). I will discuss this methodology in chapter 2.

In order to inform and to situate the project, I conducted a review of research literature on existing therapeutic computer-based systems. I specifically focused on how they motivate children to conduct repetitive exercises. As well, I reviewed the research literature regarding systems that employ the combination of living media and digital components for the purpose of engaging users. I will present a synthesis of this background research review in chapter 3, with a more detailed set of system reviews in Appendix A.

In chapter 4, I will present and discuss a series of design decisions based on the synthesis from the research literature review. This will constitute a *design rationale* for a digital living media system that motivates children to perform target activities in their home setting.

In chapter 5, I will present an iterative design process (employing the methodology of Participatory Design with Proxies), which resulted in the development of three working prototypes for *Rafigh*. The methodology of Participatory Design requires the inclusion of stakeholders in the design process

(Hourcade et al., 2014; Frauenberger et al., 2012a). In this chapter (and in more detail in Appendix B), I will provide the rationale for using this methodology; it is recognized as an effective method for designing digital systems for children with disabilities, and incorporates input from stakeholders (Hirano et al., 2010). I include Speech Language Pathologists (SLPs), teachers, parents and children in the iterative design of and in the evaluation of the prototypes.

I will present the evaluation results of the final *Rafigh* prototype in chapter 6, derived on the basis of a user study consisting of two case studies conducted in participants' homes. The objective of this evaluation will be to answer several research questions including, (i) to what degree (if any) will using *Rafigh* support the use of target applications (i.e., therapeutic and learning applications) in children?; (ii) to what extent (if any) will including the mushrooms engage the children by incorporating the dynamics of empathy and responsibility into the interaction?; (iii) to what extent (if at all), will the children and their parents grasp the relationship between engaging in target application use and the feedback from *Rafigh*?; (iv) to what extent (if any) will its use create collaboration and communication within the family setting?; and finally, (v) how will the children and their parents experience ambient interaction with *Rafigh* and respond to the slow changes in the mushrooms?

I will conclude by discussing the research results and identifying future directions in chapter 7. I believe this dissertation provides the basis for several directions for future research in service of the goal of developing more effective persuasive computer-based intervention systems.

Chapter 2
Research through Design

I respond to the question of how can computer-based systems better motivate children to use targeted applications that support learning and therapeutic outcomes in the home setting? In this chapter, I will first describe the research problem and my motivation for addressing it (section 2.1). I employ a *Research through Design* (RtD) methodology to frame all the research activities that follow. RtD is a research methodology that supports experiential inquiry into a research space through the iterative creation and evaluation of artifacts (Zimmerman et al., 2007). I will describe RtD in section 2.2 and in section 2.3 describe four criteria through which knowledge outputs of a RtD research project can be evaluated. I will present my rationale for adopting the RtD methodology in section 2.4 and in section 2.5 describe how I specifically applied it here.

2.1 Research Problem

In recent years, a large number of computer applications have emerged that support a wide range of desirable outcomes for children. These include applications that support learning (see section 3.3.1) and applications that support communication and speech language therapy (see section 3.3.2 and Appendix A). The potential impact of such systems is enormous. Learning applications could supplement (or even be incorporated into) formal education and support concrete learning outcomes (Mayer, 2014; Dondlinger, 2007).

Applications that support therapy and specifically speech language therapy can also impact a large number of children with disabilities. In Canada, more than 58,000 children reported receiving special education services, half of which have been reported as services addressing speech or language difficulties (Statistics Canada, 2008). In the United States, speech, language, and hearing disorders affect 24% of all Special Education students, amounting to more than a million and a half individuals (U.S. Department of Education, 2005). Additionally, the language and speech skills that these applications aim to improve are important social tools, the use of which enables many aspects of social life such as communication, development, education, social and psychological wellbeing and employment, among many others. Thus, it is important to research and develop new technologies that can support these applications.

As I will show in section 3.3, a challenge for learning and therapeutic systems is to engage children and motive them to conduct repetitive tasks. Several therapeutic and learning systems have been developed and studied over the last few years but they have not widely penetrated the market and there is a lack of systems that motivate the use of therapeutic and learning applications in the users' home setting.

These factors provided motivation for the research question I presented at the beginning of this chapter; how can computer-based systems better motivate children to use targeted applications that support learning and therapeutic outcomes in the home setting? Addressing this question led me to the design, fabrication and evaluation of a system that combines living and digital media and is for use in the home setting. These characteristics required the adoption of a suitable methodology to frame and conduct the project.

Rafigh uses a novel technological instantiation that combines living and computational components together. *Digital living media systems,* also referred to as *moistmedia* (Ascott, 2007), *hybrid biological-digital systems* (Lamers and van Eck, 2012) or *biological displays* (Fernando et al., 2009) are computational systems that incorporate living media such as plants, animals, fungi or other living beings (i.e., microorganisms). As I will show in chapter 3, research in the design of digital living media systems used to motivate children is relatively new young and has not been explored previously. Previous research has focused on developing digital living media systems primarily for art installations, such as *Meet Eater* (Isai and Viller, 2010) and *Spore* (Easterly, 2004). Extant motivational systems for children have not incorporated living media. This means that this field is not yet at the stage when the testing of hypotheses arising from an extant theory can be performed. This requires the application of methodologies that allow for experiential inquiry. In the absence of previous research and problem formulation, the forming of the requirements is itself a knowledge production activity.

As I will describe in chapter 4, children's interaction with a digital living media system must be evaluated and analyzed *in situ*. This is because interaction with such a system is a form of meaning making in which the system and the context are mutually defining (i.e., the context in which the system is used determines its use and the system deeply influences the context in which it is used). The interaction afforded by the system is *situated* in the sense that the child's understanding of the world, themselves, and, interaction with the living being is strongly informed by their varying physical and social situations. The specifics of particular contexts greatly influence the meaning and the nature of an interaction with the living being and can support dynamics such as performativity and empathy. In addition, living media are *physical* beings; meaning that interaction with a system that incorporates them is formed by their physical characteristics and their placement in the home setting. This quality has implications both for its use by children with disabilities and its place in a network of agents comprising of the child and his or her parents, siblings, teachers, peers and other people in his or her living community.

As I will show in chapter 5, the problem domain involves multiple, sometimes conflicting factors that coexist. In the case of the current system, there is a multiplicity in the perspectives of the stakeholders. The children want to play games and engage in digital activities and their parents, teachers and adult caregivers want these games to have benefits for them and not take away from their social development and responsibility. The problem domain requires balancing these perspectives. In this way, the research question is addressing a *wicked problem*, i.e., one that is complex with many variables affecting phenomena and with changing or unstable requirements (Schön, 1983). Thus, it is important that this system is developed and evaluated in a way that is sensitive to this characteristic.

2.2 Research through Design

Research through Design (RtD) is a research methodology used by Human-Computer Interaction (HCI) researchers to conduct experiential inquiry into a design space through the iterative creation and evaluation of artifacts. In this approach, the design and deployment of prototypes, as well as, critical analysis of their affordances and implications are the primary modes of inquiry (Zimmerman et al., 2007).

In RtD, "the design activity in the form of designers' judgments is equally important to the analysis and reasoning activities that are common to all kinds of research" (Bardzell et al., 2012). The outcome of this approach is primarily research artifacts that function as "specific instantiation(s) of a model – a theory – linking the current state to the proposed, preferred state" (Zimmerman & Forlizzi, 2008).

RtD opens up space for self-reflection on the role of the researcher-designer and provides flexibility with respect to problem formulation. It encourages the use of participatory processes and incorporating input from multiple stakeholders from the beginning of the research process to help establish the design problem. RtD supports the exploration of alternatives and creating *a* possible solution that can transform the world from a current state to a preferred state (Frayling, 1993; Fallman, 2007; Zimmerman et al., 2007). Previously, researchers have identified the relevance of this approach specifically for the evaluation of interfaces designed for children with disabilities (Frauenberger et al., 2012b). While RtD has similarities, especially in the iterative processes it employs, with other methodologies, it puts specific focus on reflection throughout the research process. In *experimental research design,* the focus is on hypothesis formulation and confirmation/refutation using controlled experiments. In *engineering design research,* the focus is on the identification of design requirements and using them to find optimal solutions to a problem.

RtD supports the inclusion of multiple stakeholders' points of view and is sensitive to subjective knowledge latent in users' and their community's experience. The development of prototypes allows for the early evaluation of research ideas and the ongoing incorporation of feedback and input from users.

Prototypes can also be used as communication tools to facilitate the collection and incorporation of user feedback into the system.

2.2.1 Knowledge Outputs from RtD

Several different kinds of knowledge outputs can result when using the RtD methodology to address a research problem. Figure 1 shows the different knowledge outputs that can result from this approach. These include the generation of *research artifacts* (prototypes) that can be used by other interaction researchers, as well as, HCI practitioners as design exemplars; the observation of unanticipated effects that can contribute to theory; the collection of field data useful for future researchers; and finally, the identification of technical opportunities for engineers.

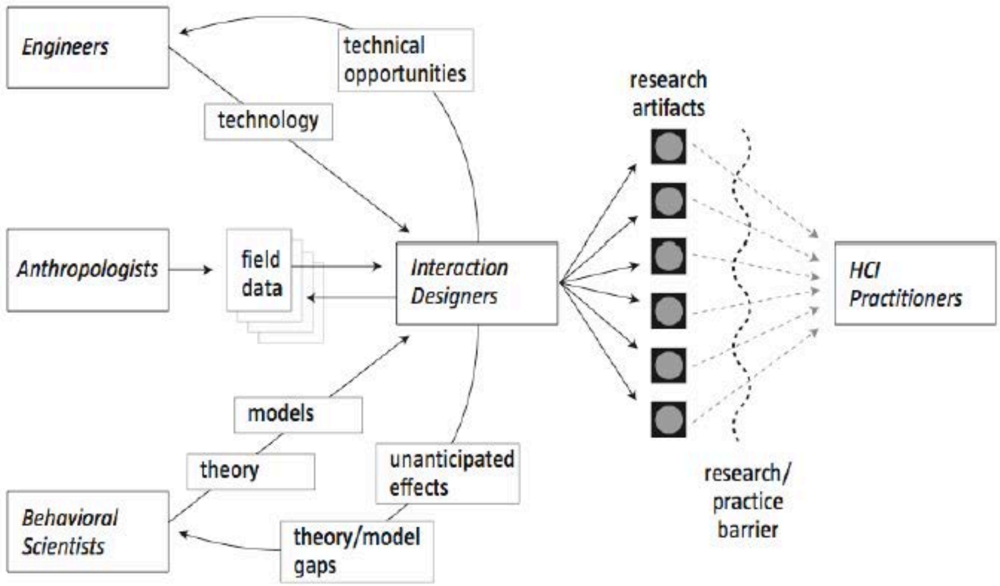

Figure 1. Possible pathways and deliverables between different researchers and practitioners that can result from a Design through Research project (Zimmerman et al., 2007).

2.3 Four Criteria for Evaluating RtD Research

Zimmerman et al. (2008) provide four criteria for evaluating the quality of research undertaken with the RtD methodology. The first criterion is the level of rigor and detail involved in the *process* of research. The interaction design researcher should provide enough detail and rationale for his or her choices such that the process can be reproduced. There may not be a single "right" answer, but instead multiple "right" answers. The aim of this approach is to find *a* right answer and to describe the process such that it can be reproduced.

The second criterion, *invention* refers to the degree to which the design is innovative and is not a refinement of previous designs. The work should be situated within the space of extant designs and the advancement that its creation brings about in the field should be articulated. This criterion is one of the differences between *research artifacts* and *product prototypes.* The central motivation behind creating research artifacts is to express and test novel research hypotheses not a commercial product.

The third criterion, *relevance,* refers to the impact that the work can have in the real world. It is important for researchers using RtD to frame their work within the real world by describing their motivation, the current situation, as well as, why the prototype brings about a preferred state of the world.

The final criterion, *extensibility,* refers to how research results, either the developed and described process or the knowledge gained through the creation and evaluation of the prototype, can be used and leveraged in future projects.

In section 7.2, I will apply these criteria to *Rafigh.*

2.4 Rationale for Using RtD

I selected the RtD methodology based on several features of the research domain and the research questions that this dissertation addresses described in section 2.1, the exploratory (vs. confirmatory) nature of the current research space; the existence of multiple confounding factors; and the situated and physical characterization of the project. In this section, I will describe why RtD is a suitable methodology to address research questions with these characteristics.

First, RtD is suitable for framing research that explores new research areas, where the field is not mature enough for the formation and testing of hypotheses arising from an extant theory. RtD supports experiential inquiry through the creation of prototypes, the observation of user interaction with them, and the elicitation of insights that otherwise would not emerge.

Second, RtD is suitable for addressing wicked problems that involve multiple stakeholders as it allows the researcher-designer to find a solution that balances perspective. The design, fabrication and evaluation of prototypes allow for gathering and incorporating user feedback arising from hands-on experience with prototypes.

Finally, as described in section 2.1, the situated and physical nature of *Rafigh* requires it to be evaluated *in situ* (i.e., in the context in which the system will be used). RtD is suitable for projects with this feature as it supports iterative design activity that results in prototypes that can be evaluated in situ.

In summary, several features of the research questions that will be addressed by *Rafigh* made the RtD methodology a suitable approach for conducting the current research project.

2.5 Application of RtD

Zimmerman et al. (2004) describe 6 possible phases that can be used to conduct a RtD project. These phases are:

- *Define*: the researcher defines the focus, in terms of intention and motivation for the research.
- *Discover*: the researcher collects data to inform the project.
- *Synthesize*: the researcher synthesizes the gathered data, extracts findings and defines opportunities.
- *Generate*: the researcher sketches, critiques and turns new ideas into prototypes that he or she then evaluates.

- *Refine:* the researcher selects specific framings and describes the form and function (behavior) of the prototypes.
- *Reflect:* the researcher reflects on every stage of the process from motivation, problem framing, preferred state to the design process.

Each phase can utilize additional methods or approaches as the researcher sees fit for accomplishing tasks and can be iterative. Table 1 provides an overview of the phases as I applied them. Additionally, the methods used in each phase and their outcomes are listed.

I will create and evaluate a series of three Rafigh prototypes using iterative design; each prototype's design will be informed by input from stakeholders and observations from the use of the previous one. These prototypes will serve as research artifacts. The design iterations with the first two prototypes provided insights into how to design and fabricate a safe a robust fourth prototype. In order to answer my research questions, I employed a small—n case study methodology to study the third Rafigh prototype in participants' homes.

Research Through Design

Phases	Methods	Outcomes	Additional Approaches	Chapters
Define				1, 2
Discover	Literature Review	Key Research Questions		3
Synthesize	Synthesis of Research Domain Literature	Design Rationale		4
Generate Refine Reflect Prototypes 1,2 Prototype 3	SLP Interviews Prototyping (Technology Probes) Observations	Analysis Results Design Concept Prototypes 1-2	PD with Proxies Field study	5
Generate Refine Reflect	Interviews Data logs	Prototype 3 Qualitative data Quantitative data Analysis of Results/ Reflection	Small-n case studies in the field ("in situ")	6, 7

Table 1. Different phases of *Research through Design* (Zimmerman et al., 2004) as applied to *Rafigh*.

2.6 Conclusion

In this chapter, I described the problem domain of the dissertation that concerns computer systems that motivate children to use target applications that provide therapeutic and/or learning outcomes. I described the RtD framework that I employ to frame the research and presented my rationale for selecting it.

Chapter 3
Literature Review

In this section, I will present a review of extant research that relates to (i) digital systems that incorporate living media; and (ii) computer-based therapeutic systems for children and how they motivate them to conduct target activities. This review comprises the Define and Discover phases of the RtD methodology and will inform the development of the design rationale, which is the next phase of the RtD methodology (Chapter 4).

3.1 Research Questions

In this dissertation I respond to the research question of how can computer-based systems better support the use of targeted therapeutic and learning applications for children? I broke this question down into the following questions:

- What does previous research reveal about existing digital systems that incorporate living media and/or embedded and tangible interfaces? (Section 3.2)

- What are the affordances of such existing systems to engage and to motivate users to conduct intervention-focused activities? (Section 3.2)
- How have virtual and/or real pets been incorporated into interventions and to what effect? (Section 3.2)
- What are the states-of-the-art of therapeutic and learning computer-based systems that require children to conduct target activities? (Section 3.3)
- What elements of these systems have been successful in achieving their goals? (Section 3.3)
- What are promising potentials in this area that are not explored yet? (Section 3.3)

3.1.1 Methodology

To identify a body of relevant research literature, I searched major computer science and engineering literature databases, including ACM Digital Library[1], Google Scholar[2], Elsevier Publishing search[3] and the International Speech

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[1] http://dl.acm.org

[2] http://scholar.google.ca

[3] http://www.elsevier.com/advanced-search

Communication Association (ISCA) archive[4]. My inclusion criteria were any publication that matched relevant keywords or topics. These topics included "living media interfaces", "living media and therapy", "living media and learning", "tangible and embedded interfaces that support intervention and behavior change in children", "serious games" and "computer-based speech language intervention for children"). I explored items that matched one or more of these topics.

Overall, I identified more than 500 items of which I included 236 in the literature review. This literature review was published as a technical report (Hamidi, 2012) and as a review paper (Hamidi and Baljko, 2013). The technical report and review paper informed sections 3.3 and Appendix A.

3.2 Digital Living Media Systems

Digital living media systems (also referred to as *moistmedia* (Ascott, 2007), *hybrid biological-digital systems* (Lamers and van Eck, 2012) or *biological displays* (Fernando et al., 2009) are technologies that comprise of computational systems that incorporate living media such as plants, animals, fungi or other living beings

[4] http://www.isca-speech.org/iscaweb/index.php/archive

(i.e., microorganisms). These systems are relatively new and can be considered as a subcategory of *tangible and embedded interfaces* (TEIs). TEIs, also known as *physical manipulatives*, *3D manipulatives* or *digital manipulatives* (Manches et al., 2009; Zuckerman et al., 2005), are characterized by electronic microcontrollers, sensors and actuators that are embedded in either existing or newly designed physical objects (Ishii, 2008). I reviewed the research literature on existing TEIs and digital living media systems in order to answer research questions relevant to *Rafigh* presented in section 3.1.

3.2.1 Tangible and Embedded User Interfaces

Tangible and embedded interfaces (TEIs) (Manches et al., 2009; Zuckerman et al., 2005) are computer interfaces that transcend the traditional desktop and screen-based system and can be characterized by electronic microcontrollers, sensors and actuators that are embedded in either existing or newly designed physical objects (Ishii, 2008). The diversity of TEIs, and the range of possibilities they provide, means they have great potential for future research and development (Ishii & Ullmer, 1997; Jacob et al., 2008). These interfaces are becoming more versatile, as novel and improved computational materials, such as digitally enhanced paper and fabrics, are developed (Buechley et al., 2008; Buechley et al., 2009). For example, Buechley et al. (2008) have developed washable electronic components that can be sewn into fabric.

There are two main categories for TEIs. In the first category are TEIs that extend or augment the traditional desktop computer configuration (i.e., by supplementing or replacing its existing interface). In the second category are stand-alone computational devices, which embed the computation so that the computer becomes an invisible platform background. Weiser (1999) foresaw this latter category as a natural direction for the future of computer interfaces and believed that computers "will weave themselves into the fabric of everyday life until they are indistinguishable from it". For instance, the *Thrifty Faucet* (Togler et al., 2009) monitors the usage patterns of a shower faucet and provides statements pertaining to water use to household members. This latter category of TEIs are related to *ubiquitous computing,* an approach to user experience design that aims to integrate computer intelligence into the "practical logic of the routine world" (Anderson, 1994), in that they could be used to implement or to interface with sensors and actuators placed in the environment. They are also related to the *Internet of things,* an approach that uses computer networks as the (often hidden) means of connecting humans, other living beings and physical objects in an information network (Ashton, 2009). The systems I review in the next subsection can be viewed as the subcategory of TEIs that incorporate living media.

TEIs support collaboration by allowing interaction between users in a shared space. There are two modes, (i) when multiple users utilize a TEI together, and (ii) when multiple users each have their own TEI unit (Fernaeus & Tholander, 2005; Suzuki & Kato, 1995). The first mode is especially conductive to collaboration, as it allows concurrent interaction, sharing control between collaborating users (Zuckerman et al., 2005). By distributing interactive objects over a large physical space, TEIs can allow users to monitor one another's gaze. The importance of following another person's gaze is shown to help achieve interaction more easily than when interacting with a graphical representation on a display (Suzuki & Kato, 1995). TEIs can also increase the visibility of users' activities to each other, allowing for better communication among them (Stanton et al., 2001; Suzuki & Kato, 1995; Fernaeus & Tholander, 2006). This characteristic has been used previously in games that aim to create awareness in children about implications of their actions and support feelings of responsibility (Antle et al., 2014).

Researchers have conjectured that TEIs can be used to engender empathy and caring, in the sense of fostering an emotional connection between the system and its user (Johnson et al., 1999). In research, Johnson et al. (1999) developed a TEI in the form of a plush toy, which had a virtual counterpart on a computer screen. When the children moved the plush toy, its movements, captured by gesture recognition software, were reflected on the virtual counterpart. Johnson et al. (1999) hypothesized that touching and moving a physical version of the virtual character helped children relate to the character more closely than having only a virtual character on the screen. Using this interface, Johnson et al. (1999) described the use of TEIs in support of empathy in the context of *sympathetic interfaces.* The researchers described how using a TEI, in the form of the plush toy, allowed them to 1) connect the effect of an action to its cause; 2) create an interface that was inviting and friendly, and; 3) simulate intelligence in the toy.

Another characteristic of TEIs is that they can be created in a wide variety of physical forms and materials, providing flexibility in the design space. This characteristic has lent itself well to the design of accessible interfaces (Zuckerman et al., 2005; Hornecker and Buur, 2006). For example, Bhat (2010) developed a tangible musical instrument for children with cerebral palsy. This instrument was designed to be playable by children with relatively poor bimanual coordination, and was intended to help develop musical ability, bimanual coordination and increase social participation. The instrument was successful during individual and group evaluations in engaging children with a wide range of abilities and provided an opportunity for them to perform music individually and in an ensemble.

Several of the characteristics of TEIs described above, such as support for collaboration, ability to create feelings of empathy and responsibility in users and flexibility in design, are promising for incorporation into a CBSLT system for children. As I will describe in chapters 5 and 6, I incorporated these elements into the developed system and evaluated their impact on user interaction.

3.2.2 Biohacking and Living Media Interfaces

In this section, I summarize extant research on the basis of three intended outcomes, biohacking and the creation of hybrid cyborgs; fostering empathetic relationships between humans and nature; and using living media as interface (i.e., to communicate information and interact with a system).

Biohacking

There is an emerging cluster of biohacking projects that aim to directly manipulate plant and animal biology, turning them into human or animal cyborgs and allowing control or monitoring of their activities. In this review, I focus on projects that involve non-human animals and plants[5]. The main goal of these systems is to control or guide the behavior of augmented animals and living beings. For example, in the *Cyborg Beetle* project, an implantable flight control microsystem consisting of multiple inserted neural and muscular stimulators, a visual stimulator, a polyimide assembly and a microcontroller are planted on a beetle, allowing for the modulation of flight control (Sato et al., 2008). Other similar projects involve the stimulation of specific brain areas of rats via inserted wireless electrodes in order to control their movements (Huai et al., 2009; Xu et al., 2004). These projects, by engaging in the direct manipulation of living beings, require a careful consideration of the technoethics involved (Luppicini, 2008; Harvey et al., 2014). These results show that a high degree of

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[5] For an interesting example of a human biohacking project see Warwick et al. (2003). Additionally Wohlsen (2011) has reviewed a number of DIY outside-the-lab biohacking projects.

control can be exercised over living media and they can be incorporate into digital systems, a characteristic that is relevant to the current system.

Empathy-Based Systems

In contrast to biohacking-focused projects, there are projects that aim to foster a nurturing relationship with living beings through technology. One strategy for doing this has been to facilitate information exchange between humans and other beings through technology. For example, the *Botanicalls* project, involved an interface that allowed plants to "communicate" with their owners, reinforcing their relationship with them. This was accomplished by embedding sensors in plants and the soil in which they were planted. A microcontroller collected data from the sensors and communicated it via Voice over IP (and later via Twitter messages), with plant owners when the plants' needs (e.g., water, soil quality) were not met (Faludi et al., 2006). A similar project, *Koubachi*, involved a mobile phone widget through which plant owners could monitor the health of their plants via several wireless sensors, monitoring moisture, light, heat, mounted on them (Bolliger and Ostermaier, 2007). With the goal of supporting increased empathy, the app allowed its users to assign names and virtual faces to their plants. These designs aim to promote longer lasting relationships with living beings that go beyond physical distance and species differences. Additionally, they have potential to support remote intimacy (Vetere et al., 2005) and contribute to the emotional wellbeing of their users through the use of technology. These projects show the potential of using living media to create feelings of empathy and caring towards the system, a characteristic that is relevant to *Rafigh*.

Living Media as Interface

Several projects have used living media as *ambient displays* and *slow media interfaces*. *Ambient Displays* move information off the screen and into the physical environment where subtle changes in form, movement, sound, color and other characteristics inform users about changes in mapped information (Wisneski et al., 1998). In a world where we are increasingly bombarded with information, designs that can communicate information subtly and non-intrusively can help reduce unnecessary cognitive load and distracting digital stimuli. Similarly *Calm Technology* aims to communicate information through subtle cues and reduce cognitive load to a minimum (Weiser and Brown, 1996). Ambient displays have the potential to "connect people through their physical environment" (Wisneski et al., 1998). *Slow media interfaces* recognize the value of systems that support reflection and a general slowing down of interaction. In his famous 2004 book, *In Praise of Slow*, Carl Honoré states that, "the great benefit of slowing down is reclaiming the time and tranquility to make meaningful connections--with people, with culture, with work, with nature, with our own bodies and minds" (Honoré, 2009). In the context of HCI and digital design, Hallnäs and Redström (2001) argue for the use of a design approach that aims to support reflection and moments of mental rest rather than efficiency in performance. The slow technology design philosophy advocates an approach in which slowness in learning, understanding and presence provides people with more time to think and reflect. A related design approach, *Slow Design,* applies this idea to the design of products and services that create space for more reflection and presence (Strauss & Fuad-Luke, 2008). This approach has recently become more popular in design practice. For example, slowLab, based in the Netherlands, has made the design of products and services that aim to explore and incorporate the concept of slow interaction a core value and has identified a series of principles for a slow approach to design (Strauss & Fuad-Luke, 2008; Fuad-Luke, 2008). The designers at slowLab have applied a slow design approach to projects in design, art, social activism and environmentalism.

Many systems are developed that implement ambient displays. For example, the *Dangling String* used an illuminated and moving wire placed in a shared office setting to display network traffic to multiple office workers: the more traffic passed through the network, the more illuminated and animated the wire became (Weiser and Brown, 1996).

Another example of an ambient display is *ambientROOM* that used ambient lights, sounds, movement and airflow in an augmented office space to convey different online information non-intrusively, for example the volume of a soundtrack of bird and waterfall sounds increased based on the number of unread emails (Wisneski et al., 1998).

Several ambient displays such as *LaughingLily* (Antifakos and Schiele, 2003) and *Office Plant #1* (Böhlen and Mateas, 1998) have been inspired by nature to create displays in the form of artificial plants that are responsive to environmental factors, such as ambient noise in workplace. Since the beginning of their emergence, ambient media were seen as tools to "connect people through their physical environment" (Wisneski et al., 1998).

Several projects have explored the possibility of using living media to convey information. These projects often take the form of ambient displays and slow designs. The project *PlantDisplay* used plants to display information about the owner's daily communication with friends, collected through monitoring of phone call logs (Kuribayashi and Wakita, 2006). Plant growth correlated with the amount of communication: the more the owner communicated the more the plant grew.

The project *Babbage Cabbage* used live red cabbage plants as empathetic biological feedback display (Fernando et al., 2009). Each head of cabbage was viewed as a single organic pixel that would change color based on the pH level of an administered solution. Social and ecological information were communicated to a viewer of the system through a range of colors that the cabbage head displayed. The system was motivated by several interesting ideas, that living interfaces evoke emotions of empathy and affection in us; and that living organisms can communicate concepts pertaining to our social and ecological condition in a way that we find more meaningful.

The same research group developed an ambient empathic interface that used DNA-transformed E. coli bacteria to communicate information through the degree to which these microorganisms glow (Cheok et al., 2008). This was accomplished through using a control liquid that when added to the plates containing the E. coli bacteria made the microorganisms glow. The control module used a light sensor to monitor the glow of the bacteria and adjust the administration of the control liquid accordingly, in effect, forming a closed-loop system in which the light emitted from the microorganisms were adjusted in real-time based on input data.

The project *Spore* consisted of a live rubber tree plant connected to a specialized watering system: the tree was watered depending on the stock exchange value of a large corporation (in this case, Home Depot) (Easterly, 2004). Information about the price of the company's stock controlled the amount of water that was given to the plant (rising or falling), thus affecting the health of the plant based on the activity of the company's finances. The project ended when the plant died of overwatering, an adverse result that the artist interpreted as a "consequence that remarks upon the effects of runaway economic growth" (Easterly and Kenyon, 2005).

The project *Meet Eater* consisted of a garden of plants connected to a specialized watering system and set up with its own Facebook page, where the watering was based on the "likes" received on Facebook (Isai and Viller, 2010). The plant garden was designed as an ambient display that could communicate about the plant's social life online via its health and growth. Similar to *Spore*, the plant was overwatered due to increased activity on its Facebook page. The artist-researchers interpreted this as the plant "drowning in a sea of love and water", symbolizing the great interest in interacting and engaging with the plants.

In the *Infotropism* project, researchers developed a living plant display to support behavior change by changing the direction of its visible parts in response to specific user behaviors over time (Holstius et al., 2004). The plant was exposed to two light sources that were turned on and off in response to user behavior. The plant's visible parts would turn to the light source that was turned on for longer periods of time, causing the plant's direction to indicate which behavior was done more. A mechanical version of the system was also developed in which a robotic plant replaced the living plant. The researchers hypothesized that the living plant display would encourage users to conduct more environmentally aware actions (i.e., recycle more frequently) because of providing feedback to them about their behavior and also by embodying a compelling and engaging emotional quality. The prototypes were evaluated in a university cafeteria where they were used to motivate patrons to recycle more frequently. The researchers found that installing the prototypes was successful at increasing the amount of recycling and that the living plant variant was more effective than the mechanical version. In 13 interviews with people observed in the cafeteria talking about the prototypes, the researchers found that the plant display provided a sense of eco-consciousness in users and motivated them to recycle more in order to help plants in general.

Trap It! is a project that has used living media to implement a non-ambient interactive display to promote learning and engagement in the context of a science museum (Lee et al., 2015). It allows users to interact with single-celled phototactic microorganisms, *Euglena Gracilis*. Users interact with the microorganisms by drawing lines and creating patterns on a touchscreen that shows a screen superimposed on a magnified real-time image of the microorganisms; the user patterns are translated into light beams that are projected onto the microorganisms which sense and respond to them by changing their swimming movement and morphology. Lee et al. (2015) installed the system in a museum setting and observed 98 museum visitors, ages ranging from 3 to 50 years old, interact with it over a single day. They found that the system was generally easy to use and engaging to both children and adults. The system supported rich communication between users and afforded new artistic expression through its playful interface. The users generally played with the "doodling" activity and did not explore further games and scientific experiments that were included with the software.

Most of these projects, with the exception of *Infotropism* and *Trap It!*, were art installations and were designed as provocations, exploring notions of empathy and relationship building. Many of the above examples used living media's own existence (flourishing or in decline) as an ambient display to communicate information and engage users' sense of empathy and affection. Results from the research projects reviewed in this section are relevant to *Rafigh* as they demonstrate how living media can be incorporated into a user interface for a digital system and can be used to communicate information.

3.2.3 Benefits of Caring for Real and Virtual Pets

Previous studies have shown that interacting with living pets can have many benefits for children. Caring for pets has been shown to increase self-esteem in children (Bergesen, 1989). Many parents observe that interacting with pets gives children valuable lessons about life events (Levinson, 2001). Other positive outcomes of having a close relationship with a pet include reduced levels of loneliness (Calvert, 1989), as well as, stress and anxiety (Wilson, 1991). Previous studies have shown that interacting with pets in a clinical setting, known as *pet therapy*, can have positive therapeutic effects for children. For example, in a study of 70 hospitalized children (average age 9.8 years old), Kaminski et al. (2002) found that having contact with a pet dog once a week improved displays of positive affect, the children's heart rates and parents' ratings of the child's mood.

Hybrid Biological-Digital Games

While living pets have been present in human history for a very long time, in recent years, a few projects have combined digital elements with live animals, creating *hybrid biological-digital games.* Several benefits such as enabling care, education and interspecies awareness were pointed out in a review of these games (Lamers and van Eck, 2012). Although the review focused on games that interact with animals, the mentioned implications are relevant to *Rafigh* because both animals and plants are living media. Discussing ethical considerations of these games, Harvey et al. (2014), have argued that, for these games that use biological agents, it is essential for researchers to consider four ethical guidelines, 1) minimize the suffering of sentient creatures; 2) balance manipulation of living beings with some notion of benefit and necessity; 3) justify their work and its contributions to the public, and finally; 4) to design the games such that they are sensitive to the emotional wellbeing of their users.

Commercial Virtual Pets

Playing with pretend animals and humanoids has a long history, and ancient dolls are some of the oldest human-made artifacts found by archeologists (Arie, 2004). The idea of virtual pets that are not alive and yet exhibit some form of behavior can be traced back to mechanical animals and humanoids (e.g., Leonardo da Vinchi's *Mechanical Lion* or Jacques de Vaucanson's *Digesting Duck* (Wood, 2002)). With the advent of computer technology, "intelligent" virtual pets have emerged. These pets can consist of software–only entities which exist in virtual game worlds. Examples include the pets in computer games such as Farmville[6] and the Sims[7]. Another example is the computer game, *Black and White*[8], within which players care for and train virtual pets in a virtual world.

[6] https://zynga.com/games/farmville

[7] http://www.thesims.com

[8] http://www.lionhead.com/games/black-white/

Recently, commercial games have emerged (e.g., Skylanders[9] and Disney Infinity[10], Hero Portal[11], Angry Birds Stella[12]) in which virtual characters are connected to physical representations. In these games, the physical figurines typically do not exhibit behaviors and are only used to unlock virtual data in a game world. I believe the toy designers have recognized the potential for commercialization of creating emotional bonds between the children and the characters in the games by using the TEIs.

Additionally, there are commercial virtual pets that have a physical (hardware) and a virtual (software) component that make them interactive in terms of exhibiting pre-defined behavior and artificial intelligence. These include toys, such as the Tamagotchi[13], AIBO[14], Furby[15] and Paro[16] that consist of both

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[9] http://www.skylanders.com/

[10] https://infinity.disney.com/en-ca/

[11] http://www.jakks.com/hero-portal.html

[12] http://stella.angrybirds.com

[13] http://us.tamagotchifriends.com

[14] http://www.sony-aibo.co.uk

[15] http://www.hasbro.com/furby/en_CA/

physical components and virtual (or software) components. These toys are interactive in the sense that they are pre-programmed with behaviors in response to user input. They have to be cared for by their owner through the administration of virtual food (via software interface) and play (via software interface or physical play that is detected through embedded sensors).

Researchers have previously identified the potential downsides of these digital toys (Turkle et al., 2006; Hafner, 2000). For example, these games can confuse children and create the mistaken belief that they are real (Turkle et al., 2006). Hafner (2000) reported that children might experience negative emotions of anger, disappointment and betrayal when they realize their Furby toy was not alive and could be broken. The new version of Tamagotchi toys have a "pause" button that allows the user to avoid the pet's "death" due to lack of care, possibly in response to feedback that the previous versions were too stressful for children to play with (Bradford, 2014). People try harder to make sense out of a message when they feel they are in conversation with a social partner (Mayer, 2014; Nass & Brave, 2005; Reeves & Nass, 1996). This dynamic may be the basis for both the

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[16] http://www.parorobots.com

benefits and disadvantages of playing with virtual and real pets, on the one hand, interacting with a digital pet can possibly create the sense of interacting with a social partner for children and motivate their engagement; on the other hand, it can also lead to disappointment and confusion. Thus, from an ethical and sociotechnical point of view, it is important to consider the emotional impact of interacting with virtual and real pets on children and make sure that adverse effects, such as misunderstandings or disappointment, are mitigated.

Virtual Pets and Therapy

A small number of studies have examined the application of virtual pets in the context of therapy. Of the virtual toys mentioned above, Paro is designed for therapeutic use and is well studied (Shibata et al., 2001; Wada and Shibata, 2007). *Paro* is an artificial seal robot that was designed for use by both children with disabilities and the elderly. It was designed to exhibit intelligent behavior, such as responding to touch and voice by vocalizations and movements. In studies conducted with Paro, participants were able to hold and care for (e.g., groom and virtually feed) the robots. The researchers hypothesized that the pleasurable sense of touching and hugging the robots, as well as, their behavior would have positive empathetic effects on the users. In a preliminary study with children (ages 2 -15 years old) at a hospital, interacting with Paro was found to have affected the children's mood positively and to have encouraged them to communicate with each other and their caregivers (Shibata et al., 2001). Positive results were also observed when elderly participants interacted with Paro robots over time (Wada and Shibata, 2007).

The *Time to Eat* project examined the effectiveness of using software-only virtual pets to promote positive behavior change, specifically healthy eating, in children (Pollak et al., 2010). These virtual pets consisted solely of software and did not have a separate physical instantiation. Children needed to interact with the virtual pets in order to ensure the pets' wellbeing. The regularity of this interaction fits well with the need for consistency for behavior change applications. The system designers allowed pets to be chosen and named by the children so that a sense of attachment and ownership could be created between the children and the pets. During the period of use, pets requested to be fed regularly and encouraged the children to eat breakfast with them. The game was given to 53 middle school children and it was observed that children who used the game ate breakfast more frequently than children who did not use the game.

In interviews, children expressed interest in and attachment to the pet (Pollack et al., 2010).

3.2.4 Summary

In my literature review, I did not find evidence that the potential of systems that combine living and digital media to motivate children is explored prior to *Rafigh*. Previous digital living media systems, such as Spore (Easterly, 2004), Meet Eater (Isai and Viller, 2010) and Cabbage Babbage (Fernando et al., 2009), show that living media can be controlled by digital components, employed to create positive feelings of empathy and caring and used effectively to communicate information. It is clear that interacting with and caring for both virtual pets and real pets can have potential therapeutic benefits for adults and children. Users of Paro (Shibata et al., 2001) and Time to Eat (Pollak et al., 2010) enjoyed and benefitted from interacting with virtual pets and pet therapy has been used in clinical settings for years (Kaminski et al., 2002). However, all of the extant digital living media systems that I identified are designed as art installations or provocations, not for use in therapy. Therapeutic approaches have either used only living media (e.g., animals in pet therapy) or non-living media systems (e.g., the Paro robot). I combine these two approaches to develop a novel digital living media system that can be used to motivate children to engage in therapeutic and/or learning activities.

3.3 Therapeutic and Learning Computer Applications for Children

In recent years, a large number of computer-based systems for children have emerged that aim to provide positive outcomes for their users including therapeutic outcomes and improved learning, communication and language skills. The use of digital devices, hand-held computers, tablets and desktop systems, by children is rapidly increasing. According to the results of a national survey published by the Rideout et al. (2010), in the United States 60% of children between the ages of eight to eighteen use computer applications and especially games on hand-held or console devices for an average of two hours on a typical day. In the last ten years, the percentage of children playing digital games has increased by more than 50%, and the amount of time they spend playing games has almost doubled. Given these statistics, there is a growing interest in computer applications for children that go beyond entertainment and provide positive therapeutic and learning outcomes for their users (Griffiths, 2003; Dondlinger, 2007; Mayer, 2014).

Boredom and lack of motivation are recognized as important hindrances to learning in the classroom (Bridgeland et al., 2006). Additionally, in the context of therapy and rehabilitation, demotivation is shown to negatively affect outcomes and contribute to feelings of resignation (Maclean et al., 2002; Burke et al., 2009). A growing body of research has shown that interactive computer applications and specifically computer games have the potential to motivate users to conduct repetitive target activities, a characteristic that could be employed to counter demotivation and boredom in learning and therapeutic contexts (Bergin, 1999; Griffiths, 2003). *Target activities* (TAs) refer to digital-based activities that are designed to have beneficial outcomes for the user. For example, in a vocabulary learning application, for example Super Animal Genius[17], a TA might comprise of repeating a new word and using it in a sentence. In a therapeutic application that supports speech intervention, for example ARTUR (Bälter et al., 2005), a TA might comprise of an exercise that requires the repetition of a problematic sound. TAs are designed and included in applications based on desired learning or therapeutic outcomes.

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[17] http://www.scholastic.com/superanimalgenius/

Application designers often include *means of engagement,* elements in a system's interface that aim to engage and motivate its users, to encourage children to use the applications perform TAs. Means of engagement can include gamification (Vicsi et al., 2000; Cohen et al., 1998; Bunnell et al., 2000; Brederode et al., 2005; Lan et al., 2014), engaging graphics (Hailpern et al., 2010; Bälter et al., 2005; Fell et al., 2006), virtual agents (Bernardini et al., 2013), narrative and movement (Hengeveld et al., 2009; Hummels et al., 2006), and multiplayer games (Brederode et al., 2005; Piper et al., 2006).

A popular technique, *gamification* is the process of combining gaming elements such as high scores, badges and levels with target activities (especially educational and training tasks) in order to create serious games (Kapp, 2012). *Serious games* are characterized as "games that do not have entertainment, enjoyment or fun as their primary purpose" (Chen & Michael, 2006). Zyda (2005) defines a serious game as, "a mental contest, played with a computer in accordance with specific rules, which uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives." Many of the emerging learning and therapeutic applications for children are designed in the form of serious games. Examples of serious games include ECHOES (Bernardini et al., 2013), a virtual reality game in which the user can practice turn taking and affective skills (e.g., body gesture recognition) with a virtual partner; and, Youopia (Antle et al., 2013), a hybrid tangible and multi-touch land use planning game for elementary school aged children that uses dynamic storytelling scenarios to teach children about environmental planning.

Learning and therapeutic computer applications have used a variety of *technological instantiations,* the primary computational technologies used to implement system functionality. *Computer graphics* refers to a large series of techniques to create images and video using computational tools and processes (Shirley et al., 2009). It is widely used to implement interactive applications including entertainment and learning systems. *Automatic speech recognition* (ASR) refers to a series of techniques combining signal processing, statistical modeling, and machine learning to analyze and to interpret human speech typically by deciphering input acoustic signals into phones or other linguistic elements such as syllables, words or phrases (Cohen et al., 2004). *Virtual social agents* are virtual entities that are able to utilize artificial intelligence to simulate social interaction through interactive actions based on user input (Bernardini et al., 2013).

Interactive tabletops are computational interfaces in the form of digitally augmented tables that can detect input from multiple users (e.g., gestures, touches, moving of elements on the table) and provide feedback through a shared interactive display usually projected onto the table (Dietz & Leigh, 2001; Piper et al., 2006). Finally, as described in section 3.2, *tangible and embedded interfaces* (TEIs) refer to systems that employ physical computational elements in their interfaces, including living media, which replace or supplement graphical displays (Manches et al., 2009; Zuckerman et al., 2005; Ishii, 2008); and *digital living media systems* (Lamers and van Eck, 2012; Fernando et al., 2009) are a subcategory of TEIs that incorporate living media such as animals or plants.

A subcategory of therapeutic computer systems includes systems that support speech language intervention. *Computer-Based Speech Therapy (*or *Training*) systems (CBSTs) refer to computational software (and possibly hardware) systems that are used in support of speech therapy or training (Bälter et al., 2005). I use *Computer-Based Speech Language Therapy* (or *Training*) systems (CBSLTs) to refer to computational systems that are used in support of speech *and* language therapy or training. These systems have been used previously for two main purposes (Eriksson et al., 2005), (i) as tools to facilitate interactive exercises in the absence of Speech Language Pathologists or teachers (Bälter et al., 2005; Vicsi et al., 2000); and (ii) as teaching tools that help the SLP or teacher communicate with the client, during intervention or training, using different feedback mechanisms including speech visualizations and animations of internal speech organs (Bälter et al., 2005; Öster, 1989, 1995, 2003).

I conducted a review of CBSLTs in order to understand the mechanisms that are utilized in their design and can inform *Rafigh.* The complete review is in Appendix A. I decided to focus on these systems for several reasons. First, these systems are well studied and an analysis of their features based on existing research and user studies provides insights into the design of *Rafigh*. Second, supporting the home component of speech language therapy is one of the most promising applications of a motivating system such as *Rafigh*: it can potentially impact the lives of children with disabilities such that they acquire important communication and language skills. Finally, as will become apparent in chapter 5, I originally intended to design *Rafigh* to directly support speech language intervention. However, over time, I realized the system can have broader applications and could be used to support a broader class of computer activities, including activities that support speech language intervention.

The review showed that CBSLTs that were designed for use in the home or school context (including systems designed for use in both home *and* clinic) implemented protocols based on *reinforcement theory* that emphasizes giving positive reinforcements to target behaviors (Whalen & Schreibman, 2003; Ferster, 1964; Fell et al., 2006; Koegel & Koegel, 1987). For these systems, a key requirement was that the system is engaging so that the user interacts with it and produces the targeted behavior (i.e., TA), which is then positively reinforced. In these systems, negative or non-positive reinforcement (including lack of positive reinforcement) is provided when TAs are not conducted. In contrast, CBSLTs that are designed for use in a clinical setting were based on *motor learning theory* that emphasizes the importance of repeated practice and accurate feedback (Wiepert & Mercer, 2002; Engwall, 2006). For these systems, implementing the TAs involved providing accurate automatic feedback to the user.

Additionally, for each system, its context of use influenced its design. By *context of use* I refer to the setting in which the application is designed to be used. The context of use also affects *interaction partners*. For example, in the home setting parents, siblings and caregiver can be interaction partners, whereas in the school setting teachers and peers can be interaction partners.

Finally, the review showed that the reviewed systems had different degrees of *customization* (i.e., flexibility with respect to TAs presented to each user). The review showed that in all the systems, the TAs and means of engagement were *tightly coupled*, in the sense that there was a close relationship between them. In other words, for each system, both components were developed together and it was not possible to use the means of engagement with different sets of TAs.

3.3.1 Summary

Learning and therapeutic applications use a variety of means of engagement to encourage and motivate children to conduct TAs that have beneficial outcomes. While a variety of means of engagement have been used in existing systems, the review showed that the potential of using dynamics of responsibility and empathy towards living beings as a means of engagement is not explore previously.

Additionally, I defined several characteristics of these applications including *Target Activities (*TAs*), Means of Engagement, Context of Use and Interaction Partners, Customization and Technological Instantiation.* In the next sections, I will use these characteristics to structure the design rationale for *Rafigh.*

3.4 Key Design Questions

Five key design questions emerged from the review:

1. TAs: What should be the TAs in the system?
2. Means of Engagement: What should be the means of engagement in the system?
3. Customization: How can the architecture and design of the system allow for flexibility and customization with respect to TAs?
4. Context of Use and Interaction Partners: Should the system be designed for use in the school, clinic or the home setting? Who are the children's interaction partners in this context (and who might therefore be affected by the system)?
5. Technological Instantiation: What computational instantiation should the system employ?

3.5 Conclusion

In this chapter, I presented results from the Discover phase of the RtD methodology that consisted of a literature review of extant digital living media systems, as well as, therapeutic and learning systems for children. The review showed that previous systems designed for children have used a variety of means of engagement to provide positive reinforcement to children and motivate them to perform target activities. It also revealed that there is a shortage of systems designed to motivate children to engage in target activities in the home setting. Additionally, the literature review revealed that digital living media systems have the potential to engage users and might create feelings of empathy and caring in them. Despite their potential to engage children, the literature review did not identify any projects that have used digital living media systems to motivate children to conduct target activities. The literature review helped me to formulate five design questions that I will address in the next chapter.

Chapter 4
Synthesis of Research Domain Literature

This chapter presents the Synthesis phase of the RtD methodology, which culminates in a design rationale. The design rationale is a series of design decisions and their justifications, provided in response to the key design questions raised in the preceding RtD phase (chapter 3).

4.1 Design Questions and Decisions

4.1.1 Target Activities (TAs)

Design Question 1: What should be the TAs of *Rafigh*?

Design Decision 1: *Rafigh* will include TAs that support a variety of learning outcomes and language skill improvements based on reinforcement theory.

Rafigh will be a motivating system that encourages children to use a variety of target applications. In this approach, *Rafigh* will provide positive reinforcement to its users by rewarding them when they complete a series of TAs that are implemented by target applications.

As a motivating system, Rafigh can be used to support a variety of TAs. The literature review showed that a large number of digital learning and therapeutic applications for children exist that could bring about positive outcomes and support learning and different forms of therapy, including speech language intervention. Given the importance of these outcomes, in this project, I use Rafigh to motivate TAs that have learning and/or therapeutic outcomes. Further, *Rafigh* will be used to encourage each child or small group of children to use a suite of TAs that are specifically selected for them by their teacher or parent/guardian (Design Decision 3).

4.1.2 Means of Engagement

Design Question 2: What should be the means of engagement in *Rafigh*?

Design Decision 2: *Rafigh* will use a digital living media system to incorporate dynamics of responsibility and empathy as means of engagement.

The literature review showed that previous digital systems have used a variety of means of engagement, including ASR (e.g., Bälter et al., 2005; Vicsi et al., 2000), virtual agents (e.g., Bernardini et al., 2013), and gamification (e.g., Piper et al., 2006; Bunnell et al., 2000), to implement interactive user experiences that motivate children to conduct TAs. However, I did not find a system that has previously incorporated living media to motivate children to engage with digital systems in the home setting.

Caring for real pets is shown in previous research to have many benefits for children including increasing self-esteem (Bergesen, 1989) and teaching valuable life lessons (Levinson, 2001). Additionally, interacting with living beings is found to reduce levels of loneliness (Calvert, 1989), stress and anxiety (Wilson, 1991), in addition to improving the mood of children who are undergoing therapy (Kaminski et al., 2002). Interacting with hybrid digital systems that incorporate living animals is found to enable care, education and interspecies awareness (Lamers and van Eck, 2012).

Additionally, previous research presented in section 3.2 showed that users are more engaged when they feel they are in conversation with a social partner (Mayer, 2014; Nass & Brave, 2005; Reeves & Nass, 1996). Different approaches such as using avatars (e.g., Bernardini et al., 2014) and virtual pets (e.g., Shibata et al., 2001) have been explored in previous research. Taking care of virtual pets is also used previously to support healthy eating (Pollack et al., 2010), as well as, to support therapy by improving children's mood and encouraging communication (Shibata et al., 2001; Frauenberger et al., 2011). Despite these benefits virtual interfaces are also found to cause confusion and disappointment in children because of their non-real behavior (Turkle et al., 2006; Hafner, 2000). Thus, I decided not to use a virtual pet or communication partner.

In the light of these results, I decided to test the potential of using living media in the form of mushrooms as means of engagement for children when using *Rafigh*.

4.1.3 Customization

Design Question 3: How can the architecture and design of the system allow for flexibility and customization with respect to TAs?

Design Decision 3: *Rafigh's* design should employ an architecture that abstracts away the particular target applications. It should decouple the means of engagement and TAs, allowing for customization of target activities based on specific user needs.

Given the diversity of learning and therapeutic applications, it is desirable for *Rafigh* to motivate children to use a variety of applications. The review showed that in most applications TAs and means of engagement were *tightly coupled*: for each system, both components were developed to work together. This meant that each system was useful for supporting one or two specific learning or therapeutic outcomes and could not support different skills or interventions at different times.

I observed that there was no compelling reason why modularization could not be applied. As described in Design Decision 1, *Rafigh* rewards children when they perform TAs. Using a modular approach allows for a child's teacher, parent or caregiver to combine *Rafigh* with other application(s) or system(s) that are focused on positive outcomes but are not necessarily engaging. *Rafigh* would then motivate the child to use these other system(s) TAs. In this way, *Rafigh* will provide flexibility in the TAs that it will support. For example, *Rafigh* can motivate children to use a target application that requires them to repeat new phrases and vocabulary, an activity that might get boring to the children after an initial period of use. When the children see that their use of the application has positive effects in Rafigh, they might get motivated to continue using the application.

This approach opens up the possibility of using *Rafigh* in combination with different suites of TAs, adapting to different users and opening up possibilities for flexibility and customization. These features support *Rafigh's* potential to support a range of learning and therapeutic activities. These features are especially valuable for assistive technology where each user has unique needs (Kintsch & DePaula, 2002).

An implication of this design decision is that the child user has to make a conceptual connection between his or her use of *Rafigh* and the other target application(s). Whether this is an easy cognitive task would need to be investigated through user observations and studies.

4.1.4 Context of Use and Interaction Partners

Design Question 4: Should the system be designed for use in the school, clinic or the home setting? Who are the children's interaction partners in this context (and who might therefore be affected by *Rafigh*)?

Design Decision 4: *Rafigh* should motivate children to use TAs in the home setting where the interaction partners are caregivers, parents and siblings.

The review presented in chapter 3 showed that there is a lack of motivating systems to encourage children to use learning and therapeutic applications in their homes. The majority of these systems are designed to support learning and therapy in classroom and clinical settings and under the supervision of teachers and other adult professionals (see section 3.3). There is a shortage of motivating systems specifically designed for use in the home setting where the user's most intimate family members (i.e., caregivers, parents, siblings) are included in the interaction. These are often the most important interaction partners of the child. Thus, designing *Rafigh* for use in the home setting addresses an unfulfilled need.

4.1.5 Technological Instantiation

Design Question 5: What computational instantiation should *Rafigh* employ?

Design Decision 5: *Rafigh* should be a TEI and employ an ambient display.

The computational instantiation of the system is a key decision. The literature review showed that TEIs have many characteristics that make them an attractive choice for systems for children with various abilities. Due to their persistence and embodiment, they support collaboration and engagement during interaction (Fernaeus & Tholander, 2005; Suzuki & Kato, 1995). They have been used previously to effectively communicate changes in system state through ambient displays (Kuribayashi and Wakita, 2006; Fernando et al., 2009; Isai and Viller, 2010). They are physically more expressive and flexible than traditional desktop interfaces, allowing for the inclusion of emotional and ludic cues that could be engaging for the child (Johnson et al., 1999). This flexibility can be used to make systems accessible to more users with a variety of disabilities (Hengeveld et al., 2009; Hummels et al., 2006; Bhat, 2010). Because of these features, I chose to design *Rafigh* as a physical embedded system (i.e., a TEI) with an ambient display.

The literature review showed that still the majority of systems developed to support language learning and intervention are implemented as desktop computer applications (see Tables 9 and 10 in Appendix A). A small number of systems are implemented as tabletop and tangible systems. Tangible and embedded systems have previously proven to be successful in engaging children with disabilities (Hengeveld et al., 2009; Hummels et al., 2006; Bhat, 2010).

4.2 Conclusion

In this chapter, I presented the results from the Synthesis phase of RtD methodology, which comprised of the design rationale for *Rafigh*. It consisted of the following design decisions:

1. *Rafigh* will motivate children to use target applications that support communication skills and learning.

2. *Rafigh* will use a digital living media system to incorporate dynamics of responsibility and empathy as means of engagement.
3. *Rafigh's* design will employ a modular architecture in which it can be used with a variety of TAs.
4. *Rafigh* will support intervention in the home or school setting, where the interaction partners are caregivers, parents and siblings.
5. *Rafigh* will be a TEI and employ an ambient display.

In the next chapter, I will use the design rationale to develop and to evaluate several prototypes of *Rafigh*.

Chapter 5 Iterative Prototype Design, Implementation and Evaluation

In this chapter, I present work conducted for the Generate, Refine and Reflect phases of the *Research through Design* methodology, which consist of the design, fabrication and evaluation of three iterations of a prototype. I start by describing the design concept and how I used it to gather information to inform the first prototype (sections 5.2). Next, I describe the design and evaluation of prototypes 1 (sections 5.3), prototype 2 (section 5.4), and prototype 3 (section 5.5). This chapter reports on the prototyping *process* that culminated in the design and fabrication of Prototype 3 that instantiates the design rationale presented in chapter 4. The evaluation of the final system is presented in chapter 6.

5.1 Overall Methodology

An overview of the initial design concept and the three prototype iterations is shown in Table 2. The design rationale evolved over the duration of the dissertation research, and some later design decisions were informed by data gathered from user interaction with earlier prototypes. The discussion of the prototypes is structured by the five design questions presented in chapter 3.

Prototype	User Population / Use Context	Technological Instantiation	TAs Protocol	Means of Engagement
Design Concept	Children with SSD Home/School	Conceptual	Motor Learning Theory	Gamification
Prototype 1	Children with SSD School	TEI and desktop	Reinforce. Theory	Gamification
Prototype 2	Children with ASD / Children with no disabilities Home	TEI and tablet	Reinforce. Theory	Living Media
Prototype 3	Children with ASD / Children with no disabilities Home	TEI (connected to tablet)	Reinforce. Theory	Living Media

Table 2. Design decisions regarding the initial design concept and three prototypes.

I adopted a *Participatory Design with Proxies* (PDwP) approach, which is a variation of Participatory Design, for designing, fabricating and evaluating the prototypes. *Participatory Design* (PD) (Greenbaum and Kyang, 1991; Schuler and Namioka, 1993) is a design methodology that emphasizes the incorporation of user domain knowledge and recognizes the importance of collaborating and co-creating with users and their community. An essential technique of PD is to actively engage the user of the technology in its design. In addition to its original application for designing technologies for the workplace, PD has been applied to great advantage to many other areas of design and development including designing for users with disabilities (Kensing and Blomberg, 1998) and, specifically, designing with children with disabilities (Hourcade et al., 2014; Frauenberger et al., 2012a). *Participatory Design with Proxies* is a variation of PD in which proxies, people who are familiar with the target users or who resemble them, are used in the early stages of design to gather domain knowledge about a particular approach. The idea behind this approach is that when it is difficult or impossible to include the target user population directly in every stage of the design process, it is useful to instead include users who have familiarity with or similarity to the intended user population. This method has been used successfully in previous research with children with disabilities (Hirano et al., 2010). In Appendix B, I provide a review of projects that use different variations of PD with children without disabilities, children with disabilities and adults with disabilities.

The PDwP approach involves iterative design in which input from stakeholders about a prototype is incorporated into future prototypes. During evaluations, I engaged four different types of stakeholders. These were Speech-

Language Pathologists (SLPs), parents, and children with and without disabilities. Given the relatively small amount of text produced from the transcription of the study notes, I conducted a qualitative open-analysis of the data, in which I classified the information manually and without the use of statistical or dictionary-based tools.

5.2 Development and Evaluation of the Initial Design Concept

5.2.1 Design Concept Development

For the application of PDwP, I started with a general idea informed by the literature review (chapter 3) that described an embedded interactive digital toy to be used in support of speech language intervention for children. I used this design concept to conduct a study to gather feedback before any software or hardware component was fabricated.

5.2.2 Design Concept Development

I developed a general design concept that consisted of the following description:

> *Rafigh is an interactive digital CBSLT system in the form of a physical toy to support speech intervention for children with speech sound disorders.*

I used the above concept as a communication tool to solicit suggestions and feedback on what such a system would look like and how it could support speech language intervention practice. I kept the concept general so that users feel its specific features were open to suggestions and not already set.

5.2.3 Design Concept Evaluation

5.2.4 Method

I designed a data collection study that targeted SLPs who work with children in my target user population of children (5-13 year olds). I chose interview and focus group formats to gather data from domain experts. The importance of using social research methods and ethnographic studies to inform technological interventions is stressed in previous research (Suchman et al., 1999).

After obtaining Research Ethics Board approval, five open-ended interviews were conducted with five SLPs. Two interviews were conducted over the phone and three interviews were conducted in person. Two of the SLPs practice in Montreal and three in Toronto. The SLPs were contacted through community partners who were already known to me.

Each interview lasted between 45 minutes to an hour. For each interview, I started by asking about the intervention protocols that the interviewee employed in addressing speech language disorders with children. Additionally, I asked the interviewee to describe any current technology use (if any) in their practice. Next, I solicited ideas for design. I described the design concept and asked them for suggestions on how such a tool could be useful to their practice. Specifically, I asked their opinion on how a digital toy could best support their clinical speech language interventions.

Additionally, I organized two focus-group sessions for speech language pathologies. Both groups were based in Toronto. Three SLPs attended the first meeting and four SLPs attended the second. These sessions lasted between one and a half to two hours. In the focus group session, I presented the design concept to the SLPs and asked for feedback and comments.

For all the meetings and interviews, I took notes and transcribed them post-meeting[18]. For the focus groups, I organized the results based on each

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[18] I decided not to use audio recordings because in the past I have had difficulty with transcribing audio and feel more confident with writing down notes during meetings and asking for clarifications in case of ambiguity.

individual SLP. For both the interviews and focus groups, my unit of analysis was the individual SLP.

5.2.5 Results and Analysis

5.2.5.1 Target Activities (TAs)

The data from SLP interviews provided several insights on the potential of a CBSLT system for supporting speech language intervention, including the recognition that technology can capture children's attention, it can motivate them to complete complementary speech language exercises at home, and, it is important that automatic feedback, if provided, be accurate and consistent.

The SLPs stated they believed technology's strength was to capture the children's attention. All the interviewed SLPs stated that a digital toy that focuses on speech elicitation would be useful to their practice. However, they also stated that they believed that if unchecked, technology's ability to capture the children attention could be detrimental to therapy as sometimes the children become so engaged by a digital game or application that they get distracted and lose focus from the intervention task. One SLP commented that she prefers to use non-computational material during intervention because too much technology can be distracting for the children.

There were numerous indications in the data that the SLPs believed that a system that could engage children in repetitive intervention tasks (e.g., repeating problem sounds and words, practicing new vocabulary in new contexts, …) would be helpful for making interventions more effective. The SLPs expressed a need for a system to keep children motivated to continue speech exercises at home. Such a system would complement the intervention administered by the SLPs that consisted of diagnosing speech or language disorders, providing ongoing and customized instructions and corrective and precise feedback to the children during the intervention. The SLPs stated that these sessions should be followed by repetitive practice and exercises. They identified the children's lack of engagement and/or motivation in these exercises as a problem that the CBSLT system can address. This is in accord with the results from literature review presented in section 3.3. The SLPs believed that using such a system in the home setting could also provide automatic tracking and record keeping of exercises.

Another finding that was repeatedly present in the data was the importance of accuracy in automatic feedback that is provided to the children.

All SLPs indicated their preference for little or no feedback rather than greater amounts of feedback that is incorrect or inconsistent (i.e., providing different feedback to similar input). Quality was emphasized over quantity, especially in settings where the SLP is not present to mediate between the technology and the child. However, they stated that all speech should not be rewarded equally and the system should be able to discriminate between different kinds of input and provide some measure of progress. The SLPs indicated that experience and training is needed to be able to provide helpful and constructive feedback for each child.

5.2.5.2 Engagement

The SLPs stated that a digital toy that can sustain the children's speech exercises in the absence of SLPs would be useful. They stated that a challenge they often faced was the children's lack of engagement with speech exercises.

Additionally, the data demonstrated that the SLPs believed it is important to keep the child engaged and motivated in the face of initial obstacles encountered when intervention is introduced. They indicated that sometimes children are reluctant to speak with a new communication partner (i.e., the SLP).

The SLPs stated that, sometimes, initial engagement of children is difficult and it takes a long time to establish a relationship with them, to the point where the child starts using their speech more freely. The SLP interview data indicated the need for sustained initial efforts to establish the rapport necessary for engagement. The SLPs stated that they thought having a digital toy would be useful for children with speech delays who sometimes exhibit more ease interacting with automatic interfaces rather than with other humans.

5.2.5.3 Customization

The data indicated a need for customizability in the design, specifically an ability to switch between languages. Three of the interviewed SLPs discussed the context of multilingual communities. Working with children who are multilingual is quite common in Toronto, and in Canada more generally, due to the presence of many new immigrants. These SLPs noted that many immigrant children whose first language is not English face difficulties when moving to a new country where English is the main language. The SLPs identified this condition as a contributor to speech delays. The issue is complex, as there are barriers to parents helping with the home component of intervention. The home language is often not English, the parents and caregivers are not fluent and are not in a position to assist with speech exercises at home. Additionally, as the children grow up, they are faced with the challenge of switching between English and their home language. These challenges can place stress on interfamily relations and cause disconnect between children and their parents. School board policies oftentimes specifically encourage parents to speak and read with their children in the home language, as a support for language development. Thus, the data showed that it would be desirable for the toy to support languages other than English that both the parents and children understand.

5.2.5.4 Context of Use and Interaction Partners

The data indicated a strong need for increased practice of speech and language skills in the home setting. The SLPs emphasized the key role of close family members (e.g., caregivers, parents, siblings), as well as, peers and teachers as communication partners with whom the children can practice language and speech skills. They also stressed the importance of including SLPs and family members in the design of specific solutions that support intervention and taking into account their input and experience to inform the design of CBSLTs.

The data also showed that capturing the child's natural speech (i.e., speech spoken in the absence of the SLP) would be helpful in assessing intervention needs. One SLP records samples of her client's speech during some of her sessions. She uses these samples for future comparison of intervention outcomes and analysis of speech in the absence of the client.

5.2.5.5 Technological Instantiation

Three of the SLPs already use props such as dolls and physical toys, as well as, images and flash cards to engage children. These toys allow for the development of narrative and the engagement of the children's attention. They stressed that it is useful to have toys that when working with small children can be touched and grasped and are also durable. Two of the SLPs who were interviewed used iPads to play games that involve speech. Surprisingly, they preferred games that encourage speech through stories and play but are not specifically developed for speech intervention and have simple interfaces, (e.g., My PlayHome[19]).

5.3 Development and Evaluation of Prototype 1

5.3.1 Prototype 1 Design Process

Given results from the SLP interviews, I decided prototype 1 should function as a digital system that would support speech elicitation tasks for children, as part of a clinical intervention based on a motor learning model for speech delay or speech sound production disorders. As described previously, a key component of these interventions is the SLP asking the child to repeat problematic sounds and/or words. Following the child's speech or vocalizations, the SLP provides feedback and corrective instructions to help the child improve the target sounds and/or words.

Prototype 1 would support an existing intervention led by the SLP in the following way: the SLP would input a series of desired words and/or sounds. The system would then use this input to provide a series of audio and visual prompts to the child, encouraging him or her to repeat the target words and/or

[19] https://itunes.apple.com/ca/app/my-playhome/id439628153?mt=8

sounds. The child's input speech would be recorded and he or she would be awarded for responding to the prompts.

5.3.2 Prototype 1 Fabrication

Prototype 1 consisted of a software user interface and a hardware component. The software user interface was executed on a laptop computer that was placed next to the hardware component. The functionality of the software interface consisted of the playback of audio and graphical prompts that solicited speech from the user[20]. The laptop display showed animal pictures and prompted the user to repeat their names. I used an ASR module, the CMU Sphinx (Walker et al., 2004), to provide rudimentary feedback in terms of whether input speech received after a prompted word was recognized or not by the system. The embedded lights each corresponded to a target word. When the ASR module recognized a word, a light would be turned on. When a set of prompts was responded to successfully and the words were recognized, the bubble blower

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[20] The software interface resembled existing tablet applications designed for young children, such as *Baby, Try to Speak 1* (https://itunes.apple.com/us/app/baby-try-to-speak-1/id480123238?mt=8)

would be activated. The user had to use the physical interface together with a laptop computer that ran the speech prompts.

The hardware component was housed in a cardboard box[21]. The box was augmented with a series of lights and a bubble blower and water display that would be activated upon completion of the exercises. The bubble blower was a repurposed children's toy. I had replaced the bubble blower's push buttons with an Arduino-based digital controller, so that the toy could be activated using commands from the computer. Five LED lights were placed on the top of the enclosure. Figure 2 and Figure 3 show prototype 1 during different stages of prototyping.

[21] The box's dimensions were 25 x 20 x 40 cm and weighed approximately 1 Kg.

Figure 2. Prototype 1 with LED lights and enclosure (left) and with electronics exposed (right)

The appearance and functionality of the first prototype were deliberately left unpolished. The prototype was intended to provide a proof-of concept and concrete instantiation of the initial design ideas for subsequent discussions, to be undertaken as per the PDwP methodology. I intended to use the prototype to facilitate discussion in the home or school setting. Using working prototypes (aka *technological probes*) that do not have the appearance of a finished product to evaluate design ideas and as communication tools are recommended in previous research (Hutchinson et al., 2003; Dawe, 2006).

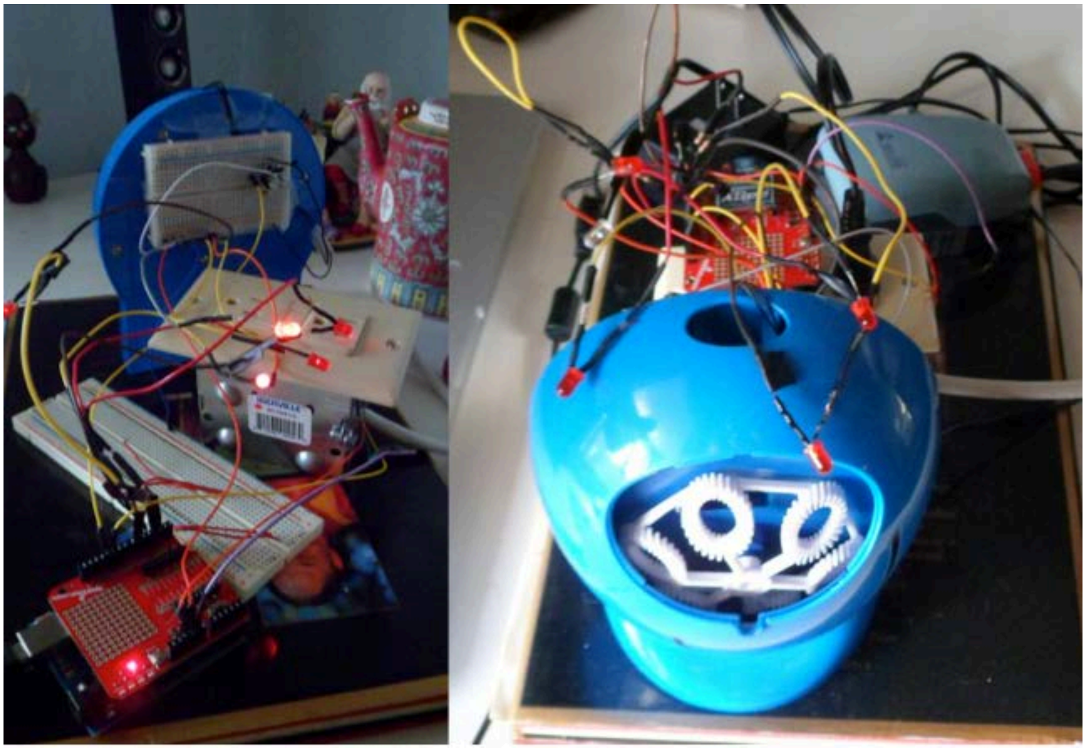

Figure 3. Fabricating Prototype 1 with LED lights and bubble-blower

5.3.3 Prototype 1 Evaluation

The evaluation was conducted as part of the RtD approach where prototypes are used to gather input from stakeholders. In the evaluation sessions, I was looking for constructive suggestions from the special education teacher and I was observing the child participant for signs of interest and engagement. As I was conducting the evaluation with a child who was non-verbal (see below), in accord with the PDwP approach, I relied on the interpretations of the special education teacher who knew the child participant and had experience working with children with speech language disorders. Using prototype 1, I investigated the design questions stated in section 5.1.

5.3.3.1 Method

I designed a user study with a child participant and his special education teacher. The study took place at the Bridlewood Jr. YMCA in Scarborough. The child participant was a 4-year-old boy with speech delay who was undergoing speech intervention.

The study was designed to have four 1-hour sessions over 4 weeks with the participant and his special education teacher. It consisted of two phases. During phase 1, Observation of Intervention Delivery, I gathered data about the intervention that was already being delivered to the child. During this phase, which lasted two sessions, I interviewed the special education teacher and observed her administering speech intervention to the child. In these sessions I did not use prototype 1.

In phase 2, Observation of Impact of Digital System, I gathered data on the participants' interaction with prototype 1. During this phase, which also lasted two sessions, I brought prototype 1 to the sessions. The prototype was not left at the school and the child only interacted with it during the sessions. During this phase I observed the child participant using the prototype. Additionally, I encouraged the teacher to comment freely on the interaction and make suggestions about how the design could be improved. During the sessions, I took shorthand notes that I transcribed later on the computer.

5.3.3.2 Results

Phase 1: Observation of Intervention Delivery

The interview revealed that the special education teacher had been working with the client for about three months on learning words and numbers. The child's family had recently emigrated from Syria and spoke Arabic at home. According to the special education teacher, one possible contributor to the speech delay was exposure to several languages at the same time.

In session 1, the special education teacher conducted speech drills with animal names and numbers with the child. She mentioned that she chose these words since they were familiar to the child and contained important target sounds. She repeated each word several times and varied the speed used to say the word. She then asked the child to repeat the words. The child made vocalizations that sometimes resembled the words but were not clear.

In session 2, the special education teacher again conducted speech drills with animal names and numbers with the child. She repeated each word several times and varied the speed used to say the words. She then asked the child to repeat the words. Again, the child responded to the teacher's prompts with vocalizations that resembled the target words but were not clear. Towards the end of the session, the child seemed restless and did not follow the teacher's instructions.

Phase 2: Observation of Impact of Digital System

During the first session of this phase, session 3 of the study, the child participant interacted only with the software component of prototype 1, as there were technical difficulties with the hardware component. During this session, the child participant was initially interested in the system. However, he became bored after about 10 minutes. When prompted for target words, the child made vocalizations but the automatic speech recognition (ASR) module did not recognize them. Additionally, when he was silent the system would appear unresponsive. He tried changing the prompts by touching the keyboards on the laptop computer but they were disabled. After 10 minutes he lost interest.

During session 3, the special education teacher made several suggestions about the software component's design. She suggested I should use brighter colors, larger images and louder sounds to make the application more interesting to the child. She also highly recommended incorporating an iPad with more immediate and pronounced feedback through video and sound to capture the child's attention. She suggested that in her experience young children were interested in graphics and lights. She suggested a more clear measure of progress (i.e., lights, sounds or graphics) would be useful to keep the child interested.

During session 4 of the study, I brought prototype 1 (both software and hardware components) to the school. During this session, the child participant interacted with prototype 1. He showed signs of interest in the water and bubble blower and was happy when bubbles were produced. However, the system did not motivate him to use his speech more. During the brief interaction (about 10 minutes) the child did not respond to any of the speech prompts. He was not interested in the software interface. Again, since the child was silent, the ASR module did not recognize any words and the system appeared unresponsive. A few times, ambient sounds were mistakenly recognized as words and lights were turned on in the interface, but the child participant did not show a sign that he noticed them. I observed that since the ASR module did not provide consistent feedback (i.e., sometimes background noise was recognized as words), it further confused the child.

During the interaction, the child participant touched every part of the system. He pulled out several of the LED lights and seemed to be fascinated by the physical box and the electronics inside. He also kept pushing keys on the keyboard of the laptop computer that was disabled. It seemed that he enjoyed touching the different parts of the system (even parts that were not supposed to be touched!).

During this session, the special education teacher made several comments and suggestions about the prototype. She stated that similar to children in the same age group, the child participant seemed to be curious about the system and its innards. She stated that it seemed the child participant also enjoyed touching different objects that have different sizes and textures (e.g., smooth LEDs). She stressed that it is important for the system to be robust and not be easily broken by the child.

She also suggested that more engaging means (such as video and sound) should be used to engage the child participant. She also commented that if the toy could be shown to other children or even if it could be used with others, its appeal might increase for the child participant.

She emphasized that the system should support intervention in the home with complementary exercises. She suggested the family of the child should be engaged in the intervention. Finally, she suggested that the toy should be designed such that it can be left in the presence of the child and not be used only during the sessions.

5.3.4 Lessons Learned from Prototype 1

5.3.4.1 TAs and Means of Engagement

The evaluation showed that the system should keep the child motivated, so that he or she would perform TAs. During phase 2, the child was only engaged for a short time by the system. While the child was initially interested in both the software interface and the bubble blower, he lost interest after a very short time. Having multiple means to keep the child engaged (i.e., both the sounds and images that accompanied the speech prompts in the software interface *and* the hardware bubble blower) was more successful than having only one of them. Additionally, using an unpolished prototype has the potential to distract children, as they focus on irrelevant components, such as the internal wiring or exposed lights.

My conjecture is that the novelty of the system wore off after the first few minutes of interaction and the child did not feel invested or motivated to continue using it. As described in section 3.3.3, previous research has shown that ideally the child should feel invested in the interface and view it as a social partner (Mayer, 2014; Nass & Brave, 2005; Reeves & Nass, 1999). This was clearly not present during the evaluation.

Based on this result, in the next iteration, I will identify and incorporate a more effective means of engagement that is different from using a bubble blower and LED lights to respond to input. I will use the new means of engagement to provide positive reinforcement when the child performs TAs.

5.3.4.2 Customization

The special education teacher stressed the importance of customization several times and said that the system should provide TAs that are specific to each user. Prototype 1 was not flexible and only provided a pre-designed set of prompts. The child could not interact with the system by using the computer keyboard. The special education teacher suggested using iPad applications that can be tweaked based on the interests or needs of the child. The system could be made more flexible by allowing for a more diverse set of TAs that the teacher can choose from based on the needs of the child.

Furthermore, the relationship between the software interface and the hardware component was unclear. During session 4, the relationship between the user's input (i.e., child's vocalizations and silence) and the system output (i.e., LEDs and bubble blower turning on) was unclear. This was partly due to the unreliability of the ASR module and partly due to the small size of the LED lights.

A challenge that needs to be addressed when a more complex software user interface is used is to establish a clear connection between change in the hardware and software modules such that there is a clear understanding of *information coupling* (the connection between two concepts and their relationship). The system should be designed such that the child clearly understands the relationship of his or her actions with respect to the system (i.e., input) to the outcomes that emerge. Don Norman refers to this concept as designing a small *gulf of evaluation* where "the system provides information about its state in a form that is easy to get" (Norman, 1988, p. 51).

Given these results, in the next prototype iterations, I will provision for a more flexible system design that can be tweaked for each user. Given the importance of the relationship between user input and system output, I will first change the design in prototype 2 such that changes in the system are clear to the user. I will revisit the need for customization and flexibility based on user needs, later on, when designing prototype 3.

5.3.4.3 Context of Use and Interaction Partners

I evaluated prototype 1 in a school setting where the special education teacher was the interaction partner of the child. The special education teacher emphasized that the system should support intervention in the home with complementary exercises. She emphasized designing both for the child *and* his or her family (especially parents). She suggested the family of the child should be involved in the intervention, something that a digital system would ideally support. Additionally, she said that if the system could be used in the presence of other children (e.g., siblings) or family members, the child might be more motivated to use it.

Given these results, I decided to design the next prototype for use in the home setting and with the user's siblings and parents as interaction partners.

5.3.4.4 Technological Instantiation

Results from the evaluation showed that the child participant enjoyed the tangibility of the physical prototype and enjoyed touching the different parts of the system. This shows the TEI approach is promising and that the system must be made more robust if it is to be used effectively in the future. Additionally, it became clear that ASR technology in its current state is not sophisticated enough to support the implementation of tasks required in my interaction scenario.

The special education teacher recommended that the system should be designed such that it can be safely left in the presence of the child without supervision and for extended amounts of time. During the evaluation, the child's touching and pulling at the prototype's physical components led to its destruction. This clearly signaled that the next prototype should be more robust and safe for the child to handle by him or herself.

Given these results, I decided to continue instantiating the next prototype as TEI as well (as opposed to a solely graphical interface). Additionally, I decided to use material and structures that support a more robust prototype. Finally, I decided to improve the safety of the system and consider and provide for all the scenarios in which the prototype might pose any danger to the child.

5.4 Development and Evaluation of Prototype 2

5.4.1 Prototype 2 Design Process

5.4.1.1 Means of Engagement

A key result from prototype 1's evaluation was that the means of engagement must be improved. In order to identify and incorporate better means of engagement, I focused on the question of what makes children excited and interested. I visited many toy stores and talked to parents informally about what their children found engaging and why. I observed many families with children at play. In particular, what stuck with me was the children's fascination with nature and animals. For instance, I observed the family of a friend, whose two children, a 7-year-old girl and a 9-year-old boy, have regular contact with family pets, a dog and two cats. The young girl in particular seeks out opportunities to come in contact with various animals and care for them. While this strong desire might not be universal in children, for me it held value as a source of inspiration and insight into a potential direction to explore in order to identify an effective means of engagement.

From these observations, a common theme emerged: Children are intrigued by living beings, especially domestic and wild animals. I decided to incorporate a living media interface to serve as means of engagement. Specifically, I chose mushrooms as the living media to incorporate into *Rafigh*.

The choice of what living media to use depended on many factors such as the degree to which the behavior of the living media can be controlled. Life can be unpredictable. It is, thus, harder to control living media than digital media. A predictable change pattern that is affected (speeded up or amplified) by interaction was needed. This could either be linear (e.g., growth) or recurring (e.g., movement or swelling). An example of a linear change pattern is apparent in *Meet Eater* (Isai and Viller, 2010) that grew during the interaction until it reached its point of maturation. An example of a recurring change pattern is evident in *Babbage Cabbage* (Fernando et al., 2009) in which the cabbage could change color according to a given state in the system. Both of these systems are described in detail in section 3.2.2.

Another factor is *feedback latency*, which is the time it takes to communicate feedback to a user. It is important to select living media that respond to user input at a suitable latency, whatever that desired latency is determined to be. There is a wide range of feedback latency in living media. For example, the response time to stimuli in animals can be instantaneous whereas the response time in plants such as a tree can take days or weeks.

5.4.1.2 Robustness and Safety

Another key result from prototype 1's evaluation was that the prototype must be robust and safe. To improve robustness, I replaced the cardboard box with a more stable and robust housing. I will describe how I fabricated the housing in section 5.4.2.4.

To address the safety of the prototype, especially when living media are included in the interface, I considered potential risks and made provisions to address them. Working with living media can potentially pose both physical and emotional health risks to the user. These risks must be eliminated or mitigated. The living media should be selected such that they do not pose any physical health risks to the user of the system. Living media, and organic material in general, if not treated properly have the possibility of toxicity. It is important to select biological materials that do not pose a danger to the users' health. For example, I considered some plants that grow fast, such as pea shoots and lentil sprouts, but there was risk of toxicity of material (i.e., soil and compost) in which they were to be planted.

Additionally, interacting with living media should not pose emotional health risks to the system's user. During interaction with living media, the life forms might die. This situation can pose emotional stress, especially to children, who might hold themselves responsible for the death. Precautions should be taken to mitigate such emotional risks. This brings up also an ethical issue where the designer is responsible for also caring for the living media themselves and avoid killing or harming them throughout the research project, as well as, when interaction is taking place. I considered and decided against using animals such as gold fish or sea monkeys as living media because their death might have caused emotional stress in the children. This choice is in accord with ethical recommendations by Harvey et al. (2014) (see section 3.2.3). To the best of our knowledge, plants and mushrooms are non-sentient beings that cannot experience suffering and *Rafigh* is intended to provide therapeutic benefits to its human users, thus, balancing manipulation of living beings with benefit and necessity.

In section 5.4.2.1, I describe in detail how I took these considerations into account when fabricating prototype 2.

5.4.2 Prototype 2 Fabrication

Given the above design goals and after considering the alternatives mentioned above, I decided to revise the design to include a living media component. The system would implement functionality that would present positive reinforcement to the child when TAs are performed. Rafigh will present stimuli, prompt the user for input, and provide feedback. The presentation of the stimuli and the prompting would be handled by a screen-based *user interface* (as in prototype 1). The feedback functionality would be implemented via living media (i.e., positive and negative feedback would be conveyed via the state of the living media). An important component of the system would be the *controller* that mediates between the software component and the living media component.

In order to instantiate this design, the following components were needed, (i) the living media (a mushroom colony - described below) connected to (ii) a micro-controlled system that can influence the living media (positively and negatively); (iii) a software controller for the micro-controlled living media, (iv) a housing for the unit; and (v) an improved version of the software interface for presenting the intervention-focused task to the children. Figure 4 shows the architecture of the system.

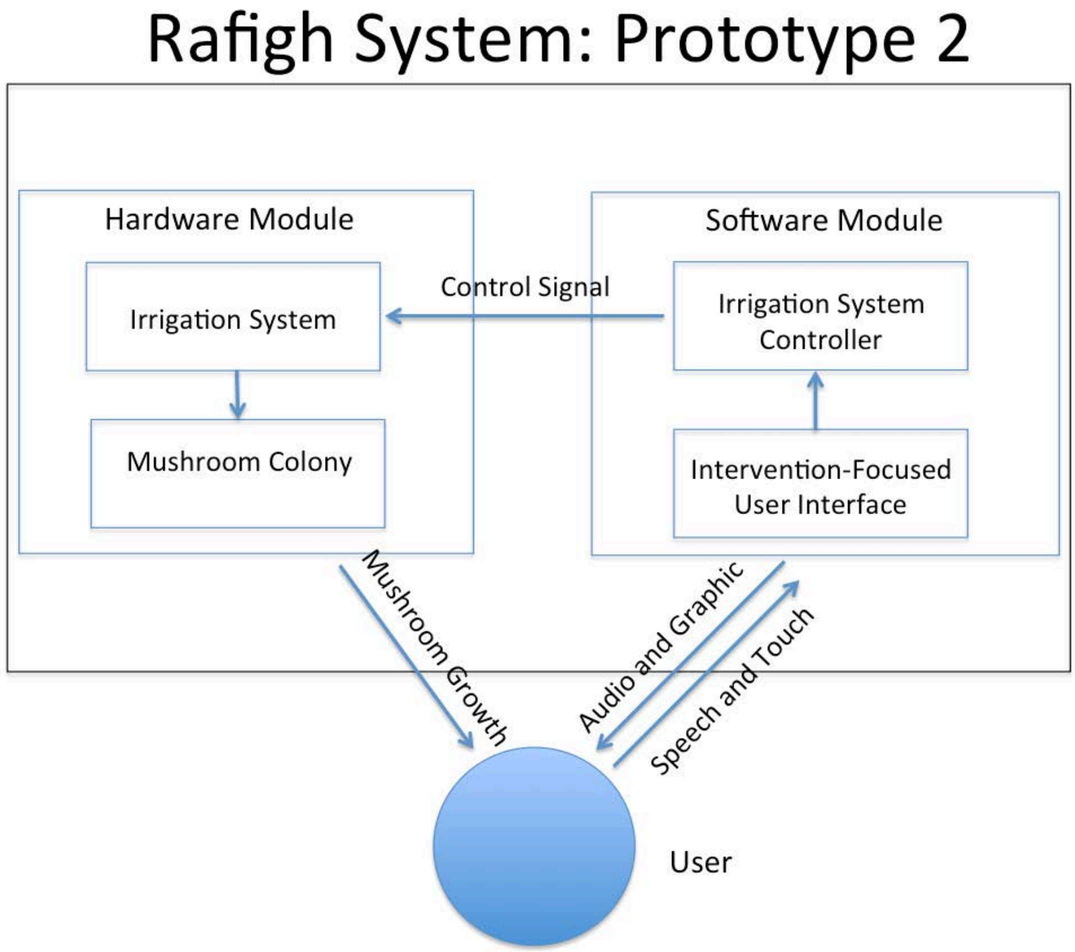

Figure 4. *Rafigh* system architecture for Prototype 2. The software module consists of two parts, a *user interface* that prompts the user for input actions; and (ii) an *irrigation system controller* that translates user input into the amount of time that the irrigation system should be activated and communicates it to the microcontroller. The hardware module consists of the irrigation system connected to the mushroom colony.

5.4.2.1 The Living Media Component: Edible Mushroom Colony

For the living media component, I decided to use edible mushrooms, such as those produced by mushroom growing kits[22]. In such kits, the organisms are housed in organic material, which is specifically developed for use in classrooms and is tested for safety for use by children. These mushroom kits consist of a growing medium, typically composed of used coffee grounds and fertilized by oyster mushroom spores. The living component of the system consists of a live

[22] At the start of the research project, for prototype 2, I used a Do-It-Yourself Mushroom Kit™ from the Back to the Roots Company (https://www.backtotheroots.com). Back to the Roots operates out of Portland, Oregon and is a widely known company working with many schools and education programs. Over the course of the research project, I identified local alternatives to the Do-It-Yourself Mushroom Kit™, and since prototype 3, have used a local alternative called ShroomBox™, which is developed in Toronto by Fungaea Company (http://fungaea.com/product/the-shroombox/).

The medium used in this product is slightly different and is composed of used coffee grounds, as well as, beer grains and sawdust from recycled wood waste. The dimensions and weight are slightly different from the Do-It-Yourself Mushroom Kit™ but the ShroomBox™ kit also produces approximately 700 grams of fresh oyster mushrooms. ShroomBox™ takes longer than the Do-It-Yourself Mushroom Kit™ to grow (typically 14-16 days).

mushroom colony (initially in the form of spores, typically the *P. ostreatus species*, aka oyster mushrooms). The mushroom spores are activated once the growing medium is soaked through an initial activation period (typically 5-6 hours). The kits can typically yield 700 grams of mushrooms in 10-12 days. The mushrooms become visible after about five days.

5.4.2.1.1 Mushroom Safety

With respect to physical health safety, the mushrooms are designed and tested to be safe for use by children and are used in many schools and homes. The medium in which they are grown is made from organic material and is safe even if ingested. The mushrooms themselves are edible. The university's Biosafety Officer confirmed the safety of the mushrooms and only identified the consumption of a large amount of raw oyster mushrooms as an unlikely source of toxicity. I incorporated the officer's feedback into the informed consent forms and as part of information provided to the parents and children who participated in the studies discussed in chapter 6.

The use of the mushrooms also suitably provisions for the emotional health of the users of the system. The mushrooms are resilient and will not die easily. They may die under harsh conditions (e.g., if left in the sun for many hours). Even when irrigation is stopped for extended periods of time, they will continue growing (albeit more slowly). Additionally, if they are not harvested for eating when they reach their prime, they will start to shrivel slowly. They demonstrate a natural cycle of growth that starts from the spores sprouting into small mushrooms, growing to their full size and then starting to shrivel if not harvested. This cycle has the potential to inspire dialogue around nature and life cycles in nature in a gentle way. In contrast to using animals, whose death could be interpreted as tragic, the mushrooms grow and are edible so that animals and insects can eat them and spread their spores in other places (Kendrick, 2002), so the sense of tragedy associated with the cycle of life and death is less intense in their case. An example narrative for the children can describe that at time of harvest the mushrooms have reached their maturity and they will die so it is OK to eat them.

I decided to design of the system to always ensure a minimum and maximum amount of water to the mushrooms so that they are not dried out or over watered as a result of the interaction. This is both to prevent the user from being neglectful (accidentally or intentionally) and, also, to protect the mushrooms from being destroyed before reaching maturity.

5.4.2.2 The Living Media Controller

I decided to control the mushrooms' growth through control of the amount of water administered to them. I used a time-controlled water pump to provide water to the mushroom twice a day. I decided to set up an algorithm to control the actual amount of water based on the amount of therapeutic activities the user has engaged in. The algorithm and its inputs are described in section 6.2. A more sophisticated system that can sense and control other variables such as temperature or moisture levels could be implemented. However, I decided to keep the system simple and only use the amount and rate of administered water to control the mushrooms' growth.

I chose to use an Arduino Uno microcontroller to control the irrigation system. The Arduino is an open-source low-cost microcontroller that is extremely popular in Maker and Hobbyist projects[23]. I used the Arduino to turn

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[23] http://arduino.cc

on and off a controllable power outlet, the PowerSwitch Tail II[24]. I initially experimented with creating my own controllable power outlet using a Beefcake relay and a Ground Fault Circuit Interrupters (GFCI) switch. However, for increased safety I decided to use the preassembled PowerSwitch Tail II.

Figure 5. Inside Prototype 2

The power outlet is connected to a small water pump, the Tom Aquatics Aqua-Lifter Dosing Pump, which is designed for use in home aquarium settings

[24] http://www.powerswitchtail.com/Pages/default.aspx

and is suitable for this project because of its small size[25]. Figure 5 shows the components inside prototype 2. The components are shown in Figure 6.

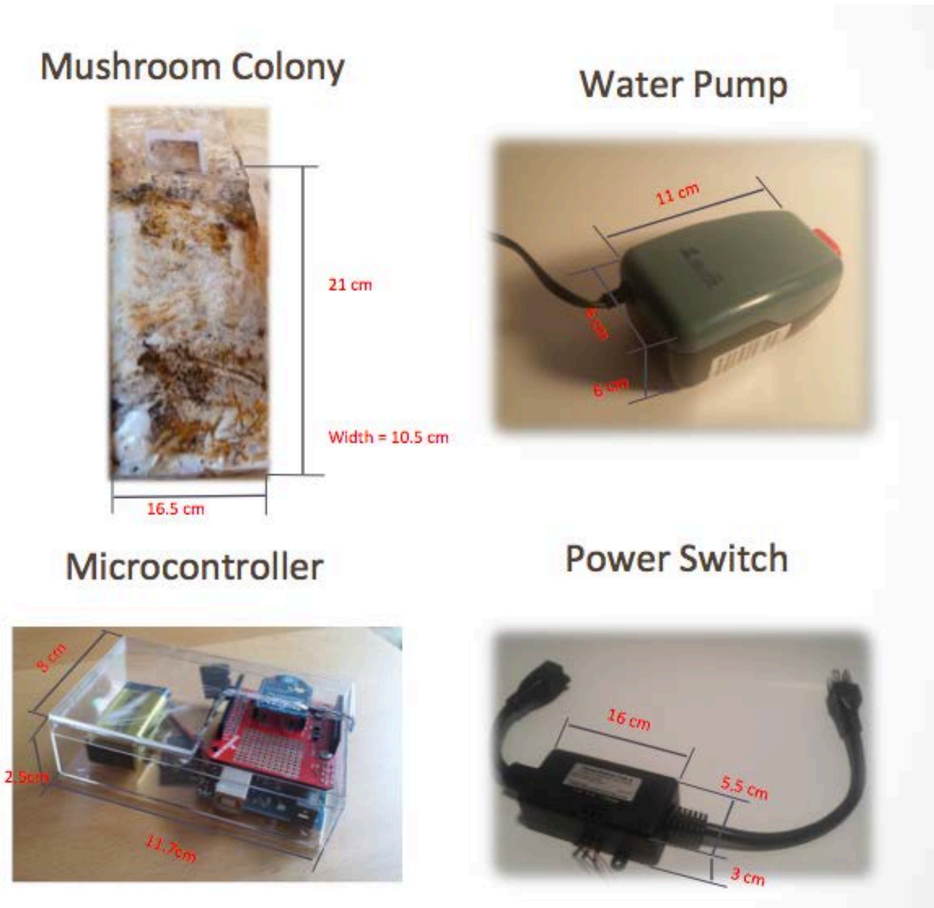

Figure 6. Components of *Rafigh*

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[25] The dimensions of the pump are 9 x 6 x 12.7 inches and it weighs 408 grams. It has a low flow rate of 189.2 milliliters per second.

5.4.2.2.1 *Discussion of Feedback Latency*

The feedback latency of the system when mushrooms are incorporated is long. The mushrooms' growth is not instantaneous. It will take 10-14 days for them to reach full bloom from the time they are first soaked in water. For the first five days, the growth is not very visible, but once it starts the effects are dramatic and small mushroom heads can grow visibly large over a short time. However, the initial period of invisible activity may pose a challenge in keeping the users engaged during the first few days of interaction. An alternative design approach to make the initial wait time shorter would be to jump-start the mushrooms (i.e., start watering them earlier). However, I decided not to use this approach, as there are potentially positive outcomes that the long latency might bring about. Specifically, the long feedback latency of the mushrooms has the potential of incorporating patience and slowness into the interaction. Whereas many digital interfaces are geared towards efficiency and fast interactions, there might be merit to develop technologies that have slowness and (the need for) patience built into them. Additionally, the challenge of waiting for something to happen over a few days might make the appearance of mushrooms more rewarding.

These features make for interesting research questions that I will formulate and investigate in the final evaluation in chapter 6.

The mushrooms' growth depends on water administered and once it starts, it continues, in varying speeds depending on the water administered, until harvest. Once the mushrooms start growing, there is not a way to put them "on pause": while their growth can be slowed down, it cannot be stopped. The growth of the mushrooms continues linearly through time (until harvest) and the user can only control the speed of growth. The idea that the mushrooms' size increases over time might be intuitive as it corresponds to the accumulating amount of time spent interacting with the system. These features point to the possibility of investigating the affordances of the feedback quality of living media in this context that I will explore in chapter 6.

5.4.2.3 Irrigation System Controller

I wrote a program in Java to control the Arduino. Two XBee Radio Series 1 modules were used to make the computer communicate with the Arduino. The Java program communicated one of three water levels—HIGH, MEDIUM and LOW—corresponding to 5, 3 and 1 seconds of irrigation, respectively. These values were determined through experimentation with the particular mushrooms that I used and are devised to avoid either drying or overwatering them.

5.4.2.4 Housing

To create the casing for prototype 2, I repurposed two iPad cases, connecting them with glue and tape, making a stable holder for the mushrooms with a placeholder for the iPad. Figure 7 shows the iPad cases being assembled and Figure 8 shows the prototype with growing mushrooms.

5.4.2.5 Software User Interface

I created the software user interface in the form of an iPad application that prompted the children with pictures of animals. This time I did not use ASR. This intervention-focused software module interacted with the irrigation system controller by sending it the amount of time the user had used it and how many input action prompts the user had seen. This data was used to calculate how much water to administer to the mushrooms.

I had designed the iPad application to be used with the mushrooms. For example, there were prompts that encouraged the user to finish the activities so that the mushroom can be watered. In this sense, there was a tight coupling between the TAs (i.e., implemented in the iPad application with the audio and visual prompts), and the means of engagement (i.e., the living media interface, the mushrooms). At this point, I conceived of the these modules of the systems to be tightly coupled and planned to develop a more sophisticated software application to be used in conjunction with the living media interface once the overall functionality of the system was established.

Figure 7. Prototype 2. Software user interface, using animal names as prompts (Left), Fabrication (top right), inside (bottom right)

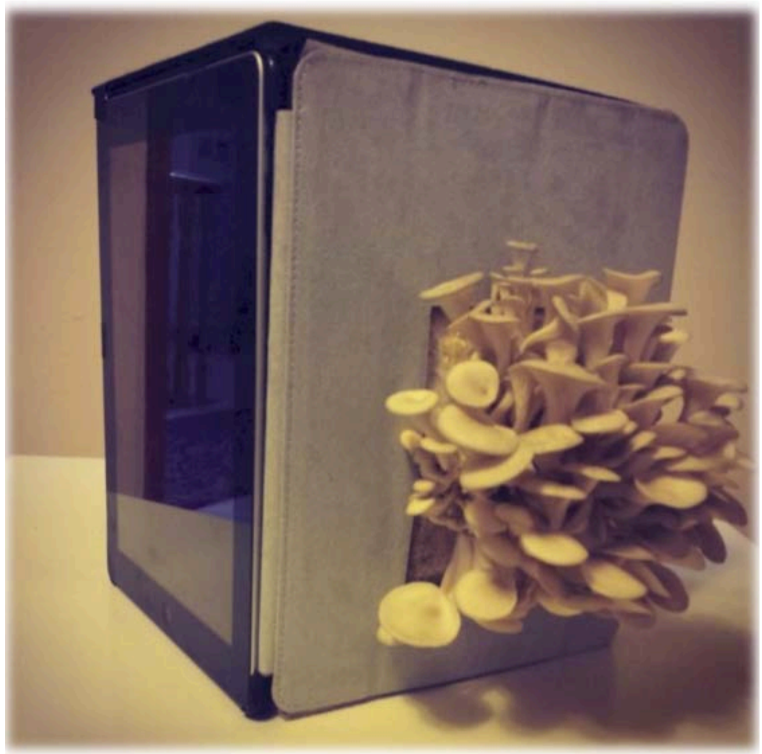

Figure 8. Prototype 2 with mushrooms and iPad

I assembled the described components into a prototype (see Figure 8). Figure 9 shows prototype 2 at different days during the mushrooms growth period.

5.4.3 Prototype 2 Evaluation

The PDwP methodology requires evaluating prototypes with representatives of the user population. To this end, I evaluated prototype 2 with two child participants and their mother. The evaluation aimed to answer several questions introduced by using living media in the home context, 1) to what extent (if any) are the children engaged by the mushrooms?; 2) Is the long feedback latency of the mushrooms a hindrance to keeping the children engaged?; 3) What are the dynamics that emerge from using *Rafigh* in the home context?; and 4) What are the implications of using a TEI and how can the physical design of prototype 2 be improved?

5.4.3.1 Method

I conducted an observational field-test of the system with two children (a 7-year-old girl and a 9-year-old boy). The children were not identified as having disabilities. These were the same participants mentioned earlier at the beginning of section 5.2.1. I described to the children and their mother that the mushrooms were going to grow over several days and left the prototype in their home for 14 days. I activated the mushroom colony by soaking it in water (as described above) shortly before delivering it to the participants' home. For this evaluation, I set the irrigation system controller to give a constant amount of water to the mushrooms everyday. I showed the software user interface to the children, but it was not used to control the irrigation system, nor were the children required to use it. As described above, the objective of this evaluation was to assess the usability of the living media component and, therefore, I decided not to focus on evaluating the software interface module.

5.4.3.2 Results

For the first two days, the children were excited about the mushrooms and checked them several times a day. They were interested in the iPad application initially but after using it for the first 15-20 minutes lost interest and wanted to use other applications on the iPad. The children's interest in the mushrooms waned after two days. There were little visible changes from day 1 to day 5 in the mushroom colony. As mentioned previously, it takes about five days for the mushrooms to start growing visibly. Once the mushrooms' growth became visible on day 6, the children's interest re-emerged with even more intensity than the beginning of the evaluation.

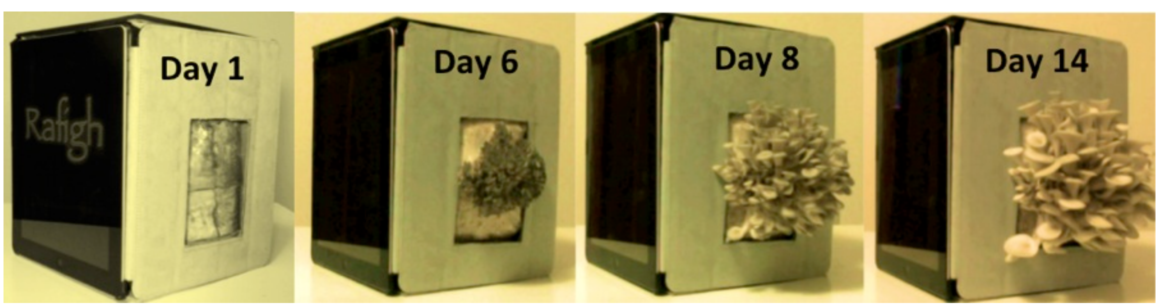

Figure 9. Prototype 2 at different stages of growth

The mushrooms grew visibly from days 5 to 14 and then stopped growing. By the end of day 14, they were starting to become dry. Figure 9 shows prototype 2 at different days during the mushrooms growth period. The figure shows that the mushrooms became visible on day 6 and continued to grow until day 14.

Once the mushrooms were visible the children checked them frequently (especially in the mornings, when the mushrooms had grown considerably since the previous evening and upon arriving home from school when a few hours had passed since they had seen the mushrooms last). The children seemed to exhibit more interest when they perceived that the mushrooms had grown faster and showed a desire to see them grow more by asking me on several occasions how large the mushrooms would grow.

The children were especially excited to show the mushrooms to their parents, school friends and whoever visited their home. Additionally, they talked about the mushrooms as personified living beings by saying, “they are happy today!” or referring to the small mushrooms as “mushroom children”. These statements demonstrated that the children had a sense of empathy towards the mushrooms.

Once the mushrooms were fully-grown, the children helped harvest them. The young girl does not like to eat mushrooms so she did not try the cooked mushrooms but the young boy ate some of them.

When showing the mushrooms to their friends, the children had moved the box and touched the housing and the mushrooms. Additionally, they liked to open the prototype housing and show the electronics inside to their friends and visitors and to describe how it worked. The structure of the prototype was stable until the end of the evaluation, but some of the glue holding the different parts was starting to come off and some of the components had moved due to the children picking up the box and moving it to show to their friends.

Finally, I observed an irregularity in the humidity of the mushroom colony over time, signaling that parts of the colony dried faster than other parts following irrigation. Thus, rather than irrigating the mushrooms a few times a day with large amounts of water, it would be better to irrigate them more frequently and with smaller amounts of water.

5.4.4 Lessons Learned from Prototype 2

5.4.4.1 Target Activities (TAs)

In this iteration, I focused on evaluating the engagement aspects of the system and did not evaluate a sophisticated set of TAs. Predictably, I observed that the children were interested in the mushrooms but soon lost interest in the limited iPad application that I had developed. I believe that the children's engagement and interest in the mushroom's growth can be leveraged as a means to create a positive enforcement when they use TAs. In the next chapter, I will investigate the extent to which children's engagement and interest in the mushrooms will translate into increased use of TAs.

5.4.4.2 Means of Engagement

Incorporating the mushroom colony into *Rafigh's* design successfully made it engaging to the children. The mushrooms captivated the children's interest during the evaluation, from the time their growth was apparent to the end of the evaluation. During the evaluation, the children checked the mushroom's growth regularly and were invested in their wellbeing (asking questions about them and showing them to visitors).

The children talked about the mushrooms as living beings by saying things like, “they are happy today!” or referring to the small mushrooms as “mushroom children”. I found these dynamics interesting as they suggest that the system can potentially elicit empathy towards other living beings, a dynamic that I will explore when evaluating prototype 3. Specifically, I will investigate to what extent do dynamics of empathy and responsibility engage the children when using *Rafigh*.

5.4.4.3 Customization

During the course of the evaluation, it became clear to me that focusing on the engagement aspects of the system was very promising. I observed that Rafigh does not need to be coupled with *one* software application (i.e., a software user interface) and it can be used in combination with one or more different target application. All that is needed is that the target application(s) have outcome states such as, “provide positive feedback” and “withhold positive feedback/provide negative feedback”. The “provide positive feedback” state could then be yoked to the controller module. I had been focusing efforts on developing a custom intervention-delivering application for the iPad, but realized that I could simply use any one of the many that already exist. The design of *Rafigh* is such that it could communicate with other existing intervention-focused applications. Thus, a key outcome was that it is possible to abstract away the TAs from the positive reinforcement (i.e., mushroom growth) element. A research question that I will investigate in the next chapter is to what extent will children grasp the relationship between using TAs and the wellbeing of the mushrooms embedded in *Rafigh*.

5.4.4.4 Context of Use and Interaction Partners

Leaving *Rafigh* at the children's home, where they could look at the mushrooms' growth whenever they liked, especially in the mornings and when they came back from school, appeared to support their engagement with the mushrooms. The children's empathy (demonstrated through empathic expressions) is possibly linked to the mushrooms being situated in the home setting, as opposed to the clinical or school settings. This feature possibly contributed to associations of *Rafigh* with pets and family members for the children. The children were excited to share their experience with others and often collaborated in explaining how the interface worked. The home setting also allowed access to Rafigh at all times, encouraging informal interaction outside of the time devoted to target application use. Taking these findings into account, I decided to keep using

Rafigh in the home context and in the next iteration investigate the extent to which it supports collaboration and communication within this context.

5.4.4.5 Technological Instantiation

Two findings emerged with respect to the technological instantiation of prototype 2. The first finding was that the tangibility and physical instantiation of *Rafigh* were promising. The children liked touching the mushrooms and sometimes moved the prototype to show it to visitors. In the evaluation, the children were curious to know how the system worked and enjoyed showing it to their peers and family. It is important to support this behavior, as it might increase children's engagement with the system. However, to keep the children safe, the electronics inside the system should only be examined and looked at in the presence of adults. Additionally, for the system to work reliably over an extended period of time, it is important that the electronic components are handled with care so that wires are not disconnected. Towards the end of the evaluation some changes in the structure of prototype 2 were visible and the glue that put the parts together was coming off. These results point to a need to improve the robustness of the prototype in the next iteration and to add locks to keep the electronic components secure.

The second finding concerns the ambient interaction that prototype 2 afforded. It took time for the living media to start showing signs of growth. It communicated information (in an ambient manner) about the state of the system to the children: their wellbeing as expressed through their growth speed and visual appearance indicated their state. This created challenges and opportunities. There was a potentially positive side to this wait: the anticipation that was built by waiting for the interface for a few days to start showing signs might have made the children vested in the mushroom colony's health and might have created an opportunity to support the children's patience by rewarding them with visible mushrooms after the initial wait.

On the other hand, after 2 days of waiting for the mushrooms, the children stopped paying attention to *Rafigh*. This shows that the initial wait and slow latency of the mushrooms might create a challenge to keep the children interested in the system. However, once the mushrooms became invisible, the children regained their interest and showed even more enthusiasm towards the system. When evaluating prototype 3, I will observe for further dynamics that the long feedback latency of the mushrooms and the ambient interaction with *Rafigh* would bring about.

5.5 Development and Evaluation of Prototype 3

5.5.1 Prototype 3 Design Process

Taking the observations from the evaluation of prototype 2 and 1 into consideration, I decided to incorporate several changes into the design of the next prototype, prototype 3.

The first change concerned the design architecture of the prototype. Based on the recommendations provided by the special education teacher about customization, when evaluating prototype 1 (section 5.4.3.3), I decided to change the design of the software module of the system such that it is limited to the irrigation system controller, rather than also including a software user interface for the child. The new controller would accept usage time data of existing target tablet applications in order to control the growth rate of the mushrooms.

This change also affects the system's TAs: rather than using one dedicated set of TAs implemented as a dedicated software user interface, I changed *Rafigh* such that it could be used in conjunction with *any* target application that was suitable for the user's needs. Figure 10, shows the new architecture of the system.

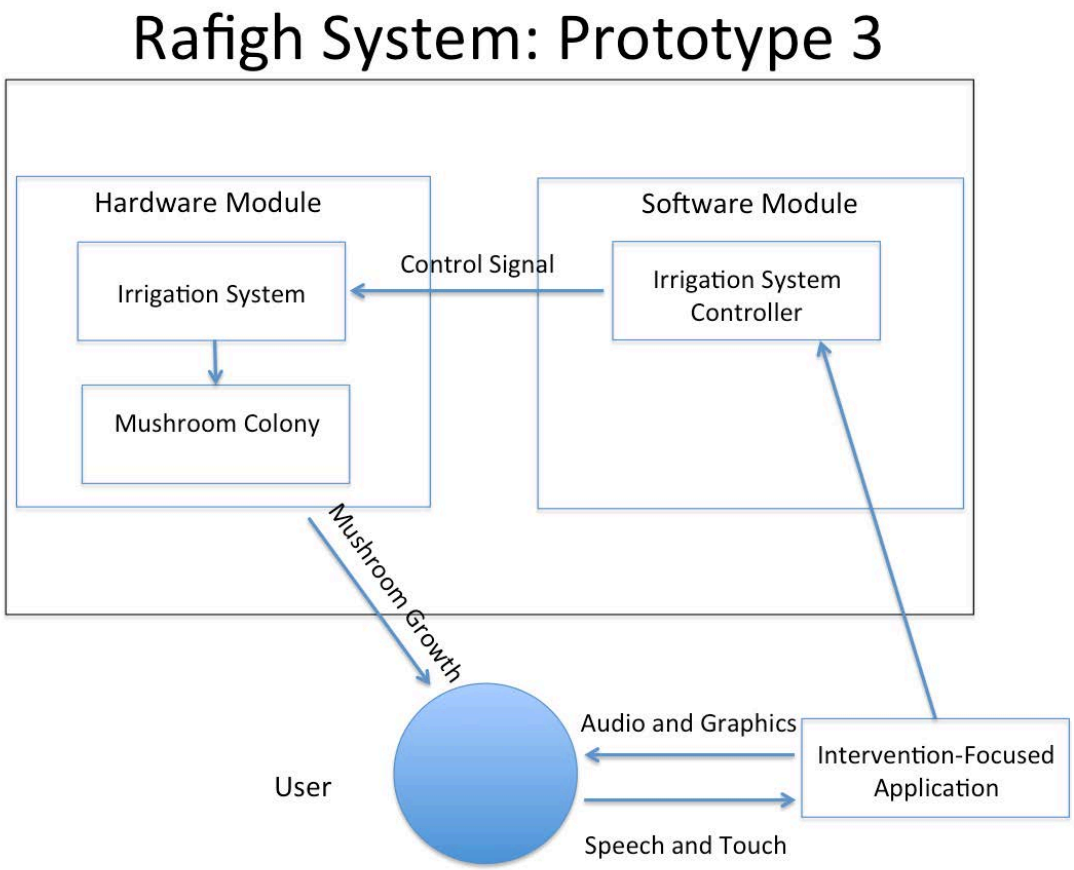

Figure 10. *Rafigh* system architecture for Prototype 3. In this design the software module only consists of the irrigation system controller that communicates with an intervention-focused application. The user interacts with an existing intervention-focused application. The amount of time spent on the application is communicated to the irrigation system controller that translates it into the frequency that the irrigation system is activated.

Another change concerned the physical housing of *Rafigh*. During the evaluation of prototype 2, child participants liked to open the prototype housing and show the electronics inside to their friends and visitors and describe how it worked. While this interaction did not damage the prototype, it underlined the need for a more robust design. As I will describe in the next section, I used new fabrication methods to achieve this goal in prototype 3.

Finally, the housing needed to be secured using a locking mechanism so that the child users could not easily access the internal components. This change should not prevent an adult participant (or the researcher) to access inside the housing. As I will describe in the next section, I added a locking mechanism to the prototype.

5.5.2 Prototype 3 Fabrication

Based on the design decisions described above, I fabricated prototype 3. The controller software was uploaded to the Arduino microcontroller that was to be embedded into *Rafigh*. As before, the controller could be accessed via a Java interface using an XBee Radio Series module. Once connected, the amount of time spent on an existing intervention application could be communicated to it. Additionally, when observing prototype 2, I realized that administering smaller amounts of water over more time would help with the moisture consistency of the mushroom colony. Thus, I made a change to the controller software such that the intervention application usage could be mapped to the *frequency* of watering, rather than the *volume* of water. In this new version, I set a constant time for watering (2 seconds of water pump activity at each watering phase) and mapped three frequency levels (LOW: water given every 12 hours, MEDIUM: water given every 6 hours, and HIGH: water given every 4 hours). In this iteration, the water level was to be input manually (using the interface described above).

Rafigh also required a more robust housing. Initially, I experimented with creating a custom housing using 3D Printing, an additive micro-fabricating technique, in which layers of temporarily melted plastic are added to a plate until a specified object is created in 3D. However, this approach was unsuccessful because of the difficulty of printing large pieces that are prone to warping (see Figure 11). After this experience I considered laser cutting, another method to create custom 3D objects that can be larger than pieces printed with a 3D printer. I decided to fabricate a custom 3D structure using custom laser-cut beaverboard parts. Beaverboard is a material made out of wood fiber compressed into sheets; it is easy to work with (e.g., when cutting, gluing, …), affordable and strong enough for the purposes of the project. I designed custom parts for the housing in Adobe Illustrator such that when put together they would form a notched box. This design was used to instruct the laser cutter to cut matching notches in beaverboard sheets. Once the laser cutter produced the parts, I connected them together using glue. I also used small hinges to connect the box top such that the mushrooms and irrigation system could be accessed. Figure 12 shows the fabrication process of prototype 3.

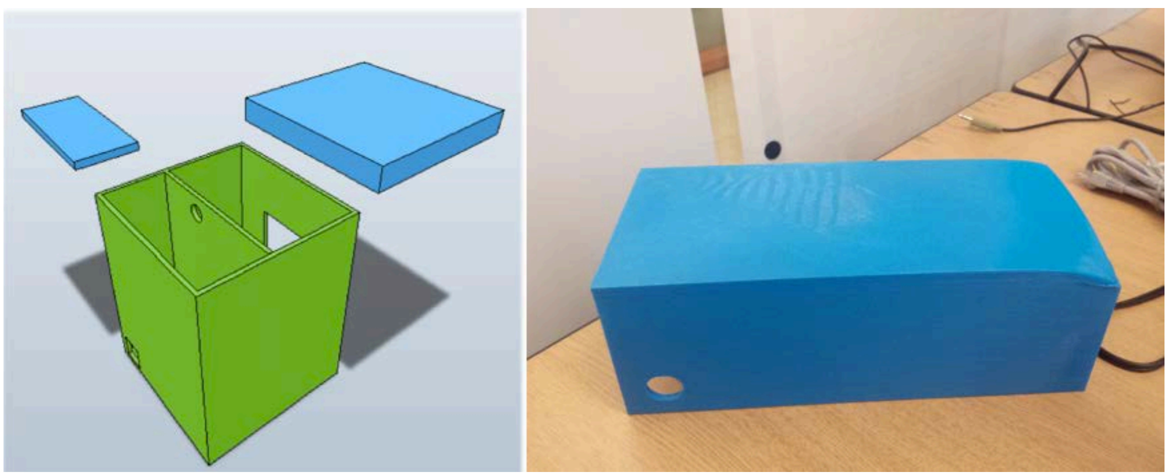

Figure 11. 3D modeling (left) and warped 3D printed *Rafigh* case (right)

To implement the improved safety measure, I added a locking mechanism so that children cannot have unsupervised access to the inside of the housing during evaluations. To achieve this, I used small locks that could be unlocked, in order to access the internal components.

Figure 12. Prototype 3 fabrication, Laser cut parts (left top), Laser cutting machine (left bottom), *Rafigh* prototype in mid-assembly (right)

I made two instances of prototype 3 that differed from each other in minor structural details. Both versions had a top cover, but differed in how the cover was designed. In one version, the cover was attached by hinges, and in the other, the cover was friction-fit to the housing (i.e., the cover had edges that overlapped the top edge of the box). Additionally, I used different locations for engraving the prototype's name and the date on which they were created. Figure 13 shows prototype 3 at different stages of mushroom growth. I used prototype 3 in the final phase of the evaluation that took place *in situ*: in the participants' homes and in the presence of their families. I will describe these user studies in the next chapter[26].

Figure 13. Prototype 3 at various stages of growth

5.6 Conclusion

In this chapter, I presented the Generate, Refine and Reflect stages of RtD, which corresponded to the design and fabrication of three prototypes. I used the initial design concept to gather suggestions and ideas from SLPs (section 5.2). They identified the need for a customizable system that can motivate the children to

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[26] Prototypes 2 and 3 were also demonstrated in a series of collaborative edible art installations, but this aspect of the work is described in Appendix C.

conduct target activities (TAs) in the home setting and engage the children's parents and peers. Using these ideas I developed three prototypes that I evaluated in an iterative process with children and a special education teacher (sections 5.3, 5.4 and 5.5, respectively). Prototype 1 rewarded children for repeating words and phrases by activating lights and a bubble blower. Its evaluation demonstrated the need for more effective means of engagement.

In prototype 2, I included a living mushroom colony whose rate of growth (controlled via automated irrigation) depended on the amount of target activities the children completed. The prototype aimed to use dynamics of empathy and responsibility towards other living beings to engage children. An evaluation of prototype 2 showed that it engaged children and that it could work with a suite of target applications. Based on these observations, I developed prototype 3 that I will evaluate in a user study presented in the next chapter.

Chapter 6
User Studies

In this chapter, I will use prototype 3 to conduct two empirical user studies *in situ* (i.e., in the users' homes). I will describe, analyze, and reflect on the interaction of users with the prototype. First, I will state the refined research questions that I investigated using the user studies. Second, I will describe the design of the study protocol and its rationale. Third, I will present and discuss the results of each of two applications of the study protocol. Finally, I will conclude with an analysis of the results with respect to the research questions.

6.1 Objective of User Studies

The user studies were conducted as a third iteration of the Generate, Refine, and Reflect phases of the RtD methodology that involve the synthesis of and reflection on findings gathered through evaluating prototypes with real users. The goal of the user studies was to evaluate prototype 3 with respect to the research questions that were presented in chapter 3 and refined in chapter 5 through the design and evaluation of prototypes 1 and 2. These research questions are:

Target Activities (TAs): (Research Question 1) To what degree does using *Rafigh* influence the behavior of children with respect to their use of "target" vs. "non-target" activities?

Means of Engagement: (Research Question 2) To what extent do dynamics of empathy and responsibility engage children when using *Rafigh* and how does using real mushrooms affect these dynamics?

Customization: (Research Question 3) To what extent do children and their parent(s)/guardian(s) grasp the relationship between using target tablet applications and caring for the mushrooms?

Context of use and Interaction Partners: (Research Question 4) To what extent does *Rafigh* support collaboration and communication within the family home context?

Technological Instantiation: (Research Question 5) What is the quality of the children's experience with respect to the slow responsivity of *Rafigh*? (Research Question 6) What is the quality of the children's experience with respect to the ambient interaction that *Rafigh* affords?

6.2 Study Design

In order to answer these questions, a study protocol was required that would satisfy the following criteria, (i) assessment of behavior change as an outcome; (ii) maintenance of high ecological validity; and (iii) accommodation for exploratory research with a highly heterogeneous user population. I will discuss each of these criteria in detail below. But first, I will provide a description of the protocol that I developed.

I decided to employ a small-n case study methodology using an AB study design. Condition A is designed to establish a baseline of tablet application use behavior prior to the introduction of the intervention (i.e., *Rafigh*). During condition A, dependent variables (both qualitative and quantitative) are measured that capture the behavior of the subjects, such as target application use times and comments made about the themes of technology, nature and responsibility. While the mushrooms in this context are domesticated and are not in their natural environment, I anticipated that their presence might create conversation around the topic of "nature". Condition B is designed to observe participant behavior during the intervention (i.e., in the presence of *Rafigh*). During this condition, the same dependent variables are measured. Upon completion of both A and B phases, a comparison of the two measurements is performed. Generally, the differences between the two phases are attributed to the introduction of the intervention. The causality, however, cannot be conclusively established, since there could be other factors (e.g., the child's development). In a variant of this method (i.e., ABA study design), the effect of uncontrolled variables can be considered to some extent, by returning to baseline and compare with both the first baseline and the intervention phases. The ABA study design typically requires longer study times and is especially useful when a strong learning effect is not present (e.g., in clinical drug trials).

In the following sections, I will discuss the benefits of using the small-n case study approach for evaluating *Rafigh*.

6.2.1 Assessing Behavior Change as an Outcome

Small-n case studies allow for the comparison of conditions that exist before and after an intervention is introduced, a feature that is suitable for evaluating behavior change (Lazar et al., 2010; Barlow et al., 2008; Barlow and Nock, 2009). Small-n case studies are designed to measure changes that affect a unit under study over time. The AB design is a common format, in which condition A is used to establish a baseline before condition B in which an intervention is introduced. As described in the previous section, the observed differences between the two phases can then be attributed to the intervention.

Small-n case studies are different from the methodology of experimental design. A between-subjects experimental study design, a commonly used format, compares an experimental group with a control group. A small-n case study compares an individual (or small group of individuals) with him or herself (or themselves). This feature means individual differences between groups are eliminated because the subject(s) is compared with him or herself, which is especially desirable when studying highly heterogeneous populations (see section 6.1.3 below). A within-subjects experimental study design, also a commonly used format, takes this approach by comparing the same group with itself under different conditions. However, a within-subjects experimental design is not suitable for comparing conditions that have a carry over effect (i.e., participation in one condition affects participation in another condition), as this can become a confounding factor in the study. Small-n case studies, attempt to minimize this effect by establishing a baseline (i.e., during the initial condition A) before introducing condition B. I will use a within-subjects small-n case study design.

6.2.2 Ecological Validity

In the context of conducting user evaluations of technological systems, *ecological validity* refers to the degree to which the environment in which the evaluation is taking place is similar to the one in which the system will be used in the future (Carter et al., 2008). Small-n case studies are suitable for conducting evaluations *in situ* (aka *in the wild*), meaning in the context in which the system will be used in reality (Carter et al., 2008; Rogers et al., 2007). In situ evaluations tend to have higher ecologically validity than other methodologies (Consolvo et al., 2007).

Conducting case studies in situ has been recommended for studying embedded systems designed for use in contexts other than ones resembling research laboratories (such as at home or in school) (Carter et al., 2008; Rogers et al., 2007). Conducting evaluations in realistic settings are believed to uncover results that might otherwise go unnoticed in a lab setting, where similar conditions might not be easy to simulate (Rogers et al., 2007, Rogers, 2011). Studies that are conducted in the lab, due to the high degree of control, are powerful for comparing a small number of variables that can be easily disentangled from each other, minimizing the effect of confounding variables (i.e., high *internal validity*). One tradeoff for this high internal validity is that some interesting phenomena and interactions might be lost and results might not be generalizable to other uncontrolled contexts (i.e., low *external validity*).

Conducting studies in the participants' homes requires establishing protocols such that privacy and comfort concerns of participants can are addressed. By entering the participants' homes or schools, the researcher is acting in a context quite different from the research lab, where set rules and procedures are usually in place (even if informally). Procedures and schedules need to be negotiated with parents, guardians, teachers and children; a process that is potentially more collaborative and participatory than the lab environment usually affords.

The current study was designed such that I did not have to visit the participants' homes every day and when possible data could be communicated to me via the phone. Additionally, I avoided installing software that would monitor the participants' activity in their homes. Finally, when the adult participants requested that they communicate the collected data verbally (rather than writing in a journal), their request was accommodated.

6.2.3 Accommodating Exploratory Research with Highly Heterogeneous Populations

Small-n case studies are generally recommended for research that is exploratory as opposed to confirmatory (Gerring, 2004). As discussed in section 2.2, the research area in which the *Rafigh* project is situated is still in the stage of experiential inquiry, making its study suitable for exploratory rather than confirmatory research.

Systems that are designed for users with disabilities typically face the challenge of targeting a highly heterogeneous user population (Kintsch & DePaula, 2002). Many people with disabilities have multiple forms of physical and mental disabilities, resulting in a heterogeneous set of different needs and priorities (Kintsch & DePaula, 2002). Also, it is often the case that such individuals have had exposure to various forms of intervention, resulting in further differences in the backgrounds of those in the target population. Methodologies that rely primarily on statistical methods to establish causal relationships may overlook the actual individual differences between the subjects of the study (Gerring, 2004). This diversity in the needs, abilities and background of users with disabilities make it desirable to use small-n case studies (Lazar et al., 2010).

6.3 Design of Study Protocol

6.3.1 Study Structure and Participants

A case study design was developed and applied twice at two different sites and with different participants. The study consisted of the following 4-phases, (i) pre-study interviews; (ii) Phase A; (iii) Phase B; and (iv) post-study interviews. In this section, I will describe the study design in more detail.

6.3.1.1 Target Participants

The unit of study will consist of a family composed of one or more parent(s)/guardian(s) and two or more children. The participants will be sought out through friends, family and community members. The parent(s)/guardian(s) must have already permitted the children to use child-appropriate digital tablet applications or be willing to permit them to use child-appropriate digital tablet applications as part of the study.

6.3.1.2 Pre-Study Interviews

The study will start with two interviews and a collaborative session. Prior to the beginning of the study informed consent will be sought from the participating parent(s) and children[27].

Interview I. The first semi-structured interview will be conducted with the parent/guardian over the phone and should take approximately 30-40 minutes. The questions were designed to gather demographic information about the family, as well as information about the current state of technology use in the family home setting. See Appendix D for a complete list of the interview

[27] The study protocol was designed in conformance with the latest Tri-Council Policy Statement on ethical conduct for research involving humans, TCPS-2 (2014). The protocol was submitted to the York University Office of Research Ethics. It was reviewed by the Human Participants Review Sub-Committee and received an approval certificate. The informed consent forms for the child participants were signed by the child's parent/guardian. Data collection that involves children requires additional steps to secure informed consent. This includes the preparation and application of a verbal assent script. The script describes the study procedure in a language appropriate for young children. I applied the protocol as designed with no further adjustments.

questions. Information about *Rafigh* and the study will be provided to the parent/guardian.

Interview II. The second open-ended interview will be conducted face-to-face with both the adult and child participants and will take approximately 30-40 minutes. The questions were designed to determine the participant's previous experience with having pets and growing flowers or plants. See Appendix D for a complete list of the interview questions.

During this interview, the study procedure will be described to the participants in further detail. If the child participants choose not to participate in the interview, the parent/guardian will be asked to describe the study procedure to them.

In this interview, the concept of a *target application* and *non-target application* will be introduced. A *target application* is an application that provides implemented target activities (TAs) as deemed appropriate for the child participants by the parent/guardian. Target applications can be therapeutic applications that include exercises to improve language skills or they can be learning apps that the parent/guardian decides are beneficial for the children to use. A *non-target application* is an app that is only used for entertainment and fun, but not for therapy or learning. While participating in the study, the child participants make the choice to spend time on (i) target digital applications, (ii) non-target digital applications, or (iii) some other pastime that does not involve using a digital application. *Rafigh* will be used to encourage the children to use more target digital applications. I recognized participating children might already have access to digital tablets and use a variety of digital applications. Allowing the children to use non-target applications allows for a more realistic setting where Rafigh would be combined with existing use patterns in the home. Therefore, I decided that the children could use non-target digital applications during the study and their use pattern should be monitored and incorporated into the data.

Collaborative Session. The interview will be followed by a collaborative session. The participants in this session will be the experimenter and the adult participant. The collaborative session must satisfy the following two goals, (i) to identify target digital applications and non-target digital applications; and (ii) to determine how data collection will be conducted.

With respect to task (i), the researcher will discuss the notion of using target applications with the parent/guardian. With this study design, the determination of the applications that *Rafigh* supports rests upon the judgment of the adult stakeholder and is decided case-by-base. After this, the parent/guardian and the researcher will together conduct a categorization exercise. This will entail examining each of the installed child-targeted tablet applications and categorizing each as either target or non-target.

With respect to task (ii), several options will be presented to the parent/guardian, 1) a monitoring software program can be installed on the tablets that the children use; 2) the parent/guardian can record the data in a log that would be collected later; or 3) the parent/guardian can report the data verbally to the researcher via the phone. After discussing the options, a decision will be made by the parent/guardian.

In addition to completing tasks (i) and (ii) described above, the adult participants took on two other crucial roles. These were, first, as unobtrusive in-situ data collectors, and, second as interpreters of information coming from the children. Since the studies will take place in the household, it is impractical and undesirable for a researcher to be present at the sessions, as this might affect the children's behavior and study results. Thus, the adult participants will be required to record and report the data. With this approach, a possibility still exists that the adult participant's bias might affect the results. However, I decided that this approach is appropriate given potential concerns about privacy and disruption that might arise when conducting the study in the home setting. This study design requires the adult participants to work closely with me.

6.3.1.3 Phase A

Phase A will be used to establish a baseline with respect to the child participants' use of tablet applications. During this time, the child participants' use of tablet applications in the home setting will be observed. The observations will take place over 5-10 sessions, each of approximately 30-60 minutes, during a period of one to two weeks. The adult participant (i.e., parent/guardian) will record the data concerning application use. The adult participant will also record any comments made by the child participants concerning the topics of "technology", "therapeutic applications", "learning applications" and "growth". The researcher will get the data from the adult participant via phone conversations.

6.3.1.4 Phase B

Phase B is the intervention phase where *Rafigh* is brought to the family home and left there until the end of the phase. During this time, the child participants' use of tablet applications in the home setting will be observed. The observations will take place over 5-10 sessions, each lasting approximately 30-60 minutes, during a period of one to two weeks. The adult participant (i.e., parent/guardian) will record the data concerning application use. The adult participant will also record any comments made by the child participants concerning the topics of "technology", "therapeutic applications", "learning applications" and "growth". I will get the data from the adult participant during 3-5 visits to the participants' home.

Based on the reported target application use, I input the water levels manually into the algorithm that controls *Rafigh's* watering mechanism (described in section 5.5.2), implementing a Wizard of Oz approach.

6.3.1.5 Post-Study Interviews

The final phase will consist of two post-study interviews.

Follow up Interview. A follow-up interview will be conducted immediately after the conclusion of Phase B. It will be a face-to-face open-ended interview with the parent(s)/guardian(s) and children (if available and willing to participate in interview). It should take approximately 30-40 minutes. I will gather information from the parent/guardian relevant to the research questions (presented in section 6.1). See Appendix D for a full listing of the interview questions.

Six-month Follow up Interview. Six months after the study, another interview will be conducted. It will be an open-ended phone interview with the parent/guardian and should take approximately 10-20 minutes. In this interview, the parent/guardian will be asked about any lasting effects from using *Rafigh* and any additional observations or reflections. See Appendix D for a full listing of the interview questions.

6.3.2 Data and Analysis

Each case study entails the collection of both qualitative and quantitative data.

Qualitative Data: The qualitative data will consist of verbal statements made by the adult and child participants. The adult participant will also report observations of children's behavior and verbal statements. This data will then be subject to thematic analysis. The analysis consists of labeling the statements, declarations and observations according to the ideas expressed. The labels are then categorized according to the research questions (presented in section 6.2.1). In the case of statements that are relevant to more than one research question, they will be placed in all the categories that apply.

The complete data set is presented in Appendix D. For each question, the analysis will draw connections between the data (including the absence of data in each category).

Quantitative Data: The quantitative data consist of the number of minutes that each child participant spent per day using applications on a per-category basis (where the categories are target and non-target application use). In addition, the ratio of use times of application categories will also be calculated.

In the case where the parent(s) do not permit/allow any non-target application use (i.e., in Case Study 2), I will only derive the former measures and not the latter.

I will use the notation $R_{Participant\ X}^{days\ in\ the\ experiment\ y-z}$ to indicate the percentage ratio of target vs. non-target application use for participant X during days y to z. I will use the notation $T_{Participant\ X}^{days\ in\ the\ experiment\ y-z}$ to indicate the average time participant X spent on target applications over days y to z. In order to show averages over multiple participants, I use the notation $T_{Participant\ X,Participant\ Y}^{days\ in\ the\ experiment\ y-z}$ for the average time participant X and participant Y spent on target applications over days y to z; and I use the notation $R_{Participant\ X,Participant\ Y}^{days\ in\ the\ experiment\ y-z}$ for the percentage ratio of target vs. non-target application use for participant *X* and participant Y during days *y* to *z*.

I will use the *split-middle method of trend estimation* (Ottenbacher, 1986; Kinugasa et al., 2004; Nourbakhsh & Ottenbacher, 1994) combined with a binomial test to analyze the data and determine whether the changes in Phase B indicated a significant effect. This test is described in several texts on single-subject data analysis for AB study design including (Ottenbacher, 1986; Kinugasa et al., 2004; Nourbakhsh & Ottenbacher, 1994) and involves drawing a trend line for the baseline phase (referred to as "celeration line") and extending it into the intervention phase. The treatment effect is then determined by comparing the proportion of data points falling below or above the celeration line for the two phases. A binomial test can determine whether the effect is significant if the number of data points above the projected line in the intervention phase is of sufficiently low probability ($\alpha = .05$) not to be attributed to chance.

Additionally, a combination of visual analysis (Parsonson et al., 1992) and time series analysis (Glass et al., 1975) will be used. Kinugasa et al. (2004) recommended combining these methods in analyzing data from single subject experiments. For the visual analysis, the *level* or the magnitude of the target variable between Phase A and Phase B will be compared. To compare the levels on a graph, for each phase, a line denoting the median of the values will be drawn on the graph (as described by Parsonson et al., (1992)).

6.4 User Study 1

6.4.1 Participants

The first case study involved three participants: a 9-year old boy (P1), a 7-year old girl (P2), and one adult participant, the children's mother (P3). A younger sibling (3 year-old) and the children's father were present during the study but did not participate. I had not met the participants prior to the study. They learned about the study through a mutual acquaintance.

6.4.2 Study Duration

The total duration of the study (not including the pre- and post-interviews) was 17 days: Phase A lasted 7 days and Phase B lasted 10 days.

6.4.3 Results

6.4.3.1 Pre-Study Interviews

Interview 1. The family, who participated in case study 1, lives in a large detached house in an upper middle class neighborhood in Toronto. Both parents have university degrees. P3 is a full time caregiver and with the help of a part time nanny takes care of the children at home. She stated that the family had previously participated in a research study that concerned the impact of environmental factors on allergic reactions in adults and children. P3 stated that she was motivated to participate in research studies since their results can be beneficial to large numbers of people. P3 stated that she and her husband believed that using technology is important for children today and said that they try to balance screen time with family activities by limiting children's use of digital tablets and motivating them to use learning applications rather than entertainment ones.

Additionally, the pre-study interview revealed that P1 and P2 use two LeapPad[28] tablets and one iPad. P1 and P2 are permitted 30 minutes of screen time in the mornings during weekdays and approximately 1 hour a day on Saturdays and Sundays, and have the choice to use either the family iPad or their LeapPad learning tablets during this time. P3 mentioned that the children had

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[28] The LeapPad tablet (http://www.leapfrog.com/) is a tablet specifically designed to accommodate digital learning activities.

prior experience with growing flowers. P3 stated that in addition to the devices used in the study, the family owns a desktop computer that is primarily used by her and her husband.

Interview 2. During the face-to-face interview, P1 and P2 said they enjoyed their previous experience with growing flowers. They did not have a pet. The study procedure, as well as, the difference between target and non-target applications, was described to them.

Collaborative Session. In the collaborative session, P3 stated that she wanted *Rafigh* to encourage the children to use more learning applications. She categorized existing applications on the iPad tablets as per Table 3. All the applications on the LeapPad were categorized as learning applications, whereas only some of the applications on the iPad were categorized as learning.

In the session, P3 understood and agreed to the data collection procedure as described in section 6.3.1. The choice was made to use P3's observations instead of a monitoring program.

Application name	**Platform**	**Category**	**Skills targeted**
Super Animal Genius	LeapPad	Learning	Animals and life science facts, vocabulary
Leapfrog Kart Racing	LeapPad	Learning	Teaches mathematical skills
T-Rex Rush	LeapPad	Learning	Reading, writing and spelling

Disney Animation Artist	LeapPad	Learning	Drawing, creativity
Inventioneers	iPad	Entertainment	Puzzle/action game
Poptropica	iPad	Entertainment	Adventure/action game

Table 3. Applications used in case study 1

6.4.3.2 Phase A

For the baseline measurement, the percentage ratio of target vs. non-target application use for 7 days of study were R_{P1}^{1-7} = 54%, R_{P2}^{1-7} = 39% and $R_{P1,P2}^{1-7}$ = 46%. Table 4 and Figures 14 and 15 show the results from this phase. For the first two days of this phase, there was an increase in the ratio of target applications used for both children (and especially P1) ($R_{P1,P2}^{1-2}$ = 62%). After the first two days, the ratio of target to non-target application use decreased for both child participants ($R_{P1,P2}^{3-7}$ = 42%).

Study Day	**P1 Application use** **Target/ Non-Target /Total (Minutes)**	**P2 Application use** **Target/ Non-Target /Total (Minutes)**	**P1 Ratio** **Target/ Non-Target**	**P2 Ratio** **Target/ Non-Target**	**Average Ratio** **Target/ Non-Target**
1	20/10/30	20/10/30	66%	66%	66%
2	25/5/30	10/20/30	83%	33%	58%
3	20/10/30	10/20/30	66%	33%	49%
4	10/20/30	10/20/30	33%	33%	33%
5	30/30/60	25/35/60	50%	41%	45%
6	30/30/60	20/40/60	50%	33%	41%
7	10/20/30	10/20/30	33%	33%	33%

Table 4. Data from Phase A of case study 1, the first column indicates the study day; the second and third columns provide application use times (both target and non-target) for P1 and P2, respectively; the fourth and fifth columns provide the ratio of target vs. non-target application use for P1 and P2, respectively; finally, the sixth column provides the average ratio of target vs. non-target applications for both P1 and P2.

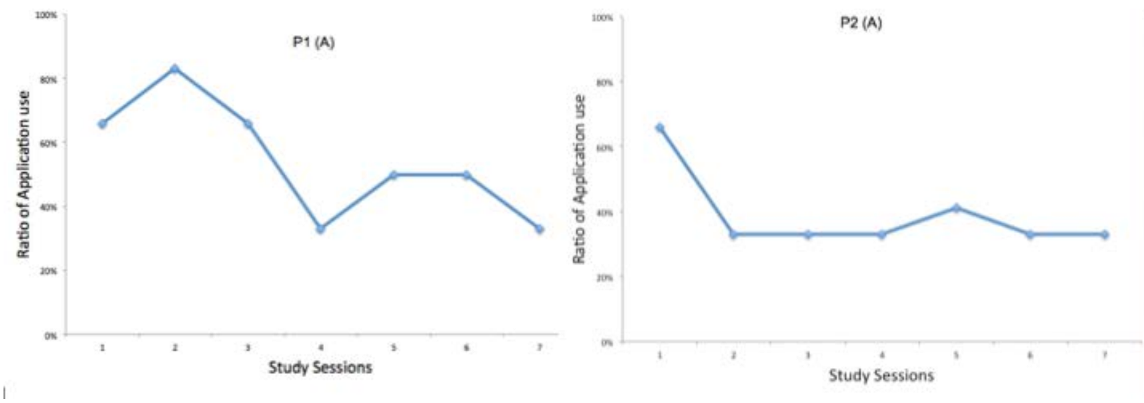

Figure 14. Graphs showing data from Phase A of case study 1. The graph on the left (a) shows data for P1, and the graph on the right (b) shows data for P2. The horizontal axes show the study sessions and the vertical axes show the ratio of target vs. non-target application use.

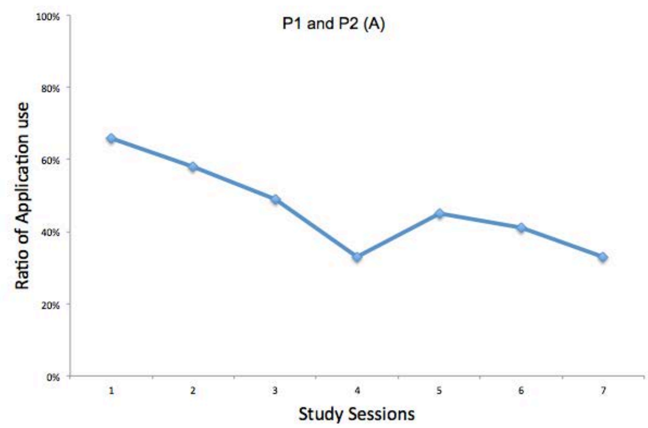

Figure 15. Graph showing data from Phase A of case study 1 for P1 and P2 combined (showing the average ratios). The horizontal axis shows the study sessions and the vertical axis shows the ratio of target vs. non-target application use.

6.4.3.3 Phase B

For the 10 days of the intervention phase, the percentage ratio of target vs. non-target application use were R_{P1}^{8-17}= 80%, R_{P2}^{8-17}= 49%, and $R_{P1,P2}^{8-17}$= 64%. Table 5 and Figures 16 and 17 show results from this phase.

On the first day of Phase B both child participants used the target applications at high levels ($R_{P1,P2}^{8}$= 83%). For the days 1-3, P1 used almost exclusively the target applications (R_{P1}^{8-10} = 89%). P1 had indicated that he had to use "more learning applications so the mushrooms grow faster" (as reported by P3). In the first day, P2 also used more target applications (R_{P2}^{8} = 83%).

However, in the next two days, she used more non-target applications (R_{P2}^{9-10} = 33%). Once the mushrooms became visible growing (day 13), the children started using more target applications than before ($R_{P1,P2}^{13-17}$= 67%). P1 continued to use more target applications until the end of the study (R_{P1}^{15-17}= 83%), whereas P2 started to use more non-target applications after day 15 (R_{P2}^{15-17}= 44%).

Once the study was completed, the mushrooms were harvested by P1 and P2, brought to the children's school to show to their peers, and then eaten by the children's parents.

Study Day	P1 Application use Target/ Non-Target /Total (Minutes)	P2 Application use Target/ Non-Target /Total (Minutes)	P1 Ratio Target/ Non-Target	P2 Ratio Target/ Non-Target	Average Ratio Target/ Non-Target
8	25/5/30	25/5/30	83%	83%	83%
9	30/0/30	10/20/30	100%	33%	66%
10	25/5/30	10/20/30	83%	33%	58%
11	20/10/30	10/20/30	66%	33%	49%
12	35/25/60	25/35/60	58%	41%	49%
13	45/15/60	40/20/60	75%	66%	70%
14	25/5/30	20/10/30	83%	66%	74%
15	25/5/30	15/15/30	83%	50%	66%
16	25/5/30	10/20/30	83%	33%	58%
17	25/5/30	15/15/30	83%	50%	66%

Table 5. Data from Phase B of case study 1, the first column indicates the study day; the second and third columns provide application use times (both target and non-target) for P1 and P2,

respectively; the fourth and fifth columns provide the ratio of target vs. non-target application use for P1 and P2, respectively; finally, the sixth column provides the average ratio of target vs. non-target application use for both P1 and P2.

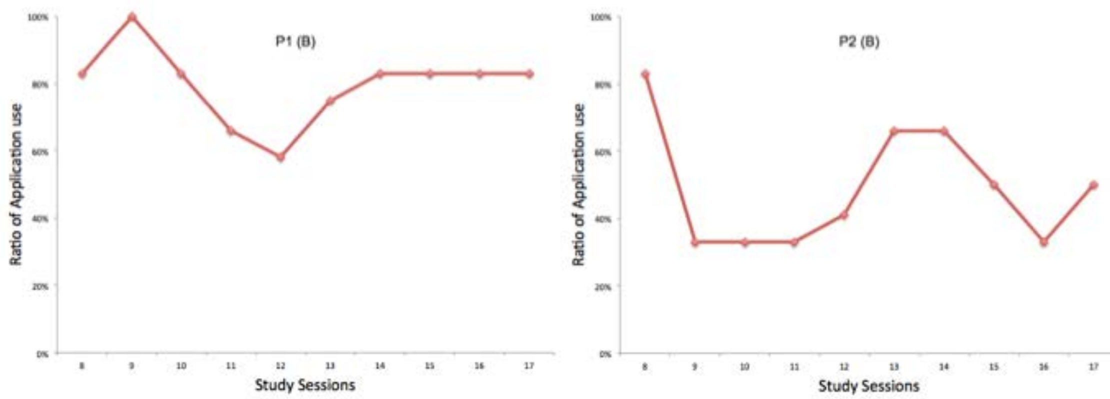

Figure 16. Graphs showing data from Phase B of case study 1. The graph on the left (a) shows data for P1, and the graph on the right (b) shows data for P2. The horizontal axes show the study sessions and the vertical axes show the ratio of target vs. non-target application use.

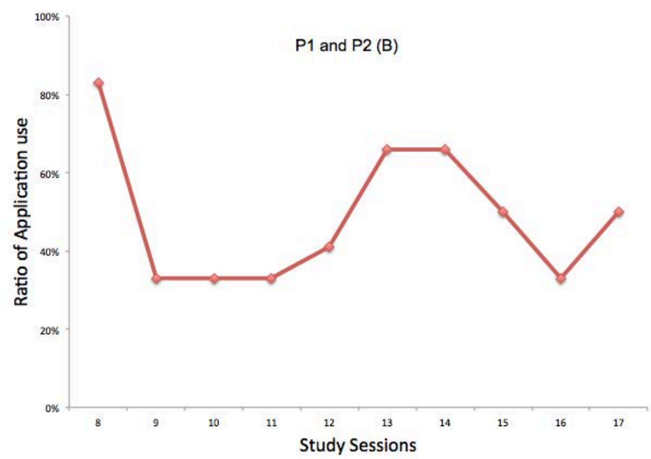

Figure 17. Graph showing data from Phase B of case study 1 for P1 and P2 combined (showing the average ratios). The horizontal axis shows the study sessions and the vertical axis shows the ratio of target vs. non-target application use.

Rafigh Operation. I initialized the mushrooms in *Rafigh*, by soaking it as described in section 5.4.2.1 the day before bringing it to the participant's home. The irrigation level of *Rafigh* changed during the study as per the protocol governing the watering level based on the ratio of target vs. non-target application use for P1 and P2 combined. The irrigation level started at the default setting of MEDIUM on day 1 of Phase B (day 8 of the study) and increased to HIGH in response to the children using more target applications ($R_{P1,P2}^{8-9}$= 77%) on day 2 of Phase B (day 9 of the study). It decreased to MEDIUM on day 4 of Phase B (day 11 of the study), in response to a decrease in R ($R_{P1,P2}^{10-11}$= 53.2%, a decrease of 23.8% from $R^{8-9}_{P1,P2}$). It increased to HIGH again on day 7 of Phase B (day 14 of the study), in response to an increase in R ($R^{12-14}_{P1,P2}$= 64.3% an increase of 11.1%) It remained HIGH until the end of the study (day 17) as the ratio remained almost the same.

6.4.3.4 Post Interviews

In this section, a summary of the data collected during the post-interviews is provided. The full dataset is provided in Appendix D.

Follow up Interview. With respect to the experience of interacting with *Rafigh* and participating in the study, all three participants expressed that they enjoyed the experience and would like to participate in future studies. P1 was interested in growing mushrooms again.

With respect to whether *Rafigh* brought about signs of empathy and responsibility in the children, P3 reported that once the mushrooms started growing (day 13), both P1 and P2 would check them first thing in the morning and when they came back from school. P1 and P2 referred to the mushrooms as "those guys" or "the little ones". Every time I visited the participant's home, P1 had several questions about the mushrooms and how they grew and reproduce. P3 believed the children had become invested in the mushrooms' health during the study. She was supportive of the study for the whole duration of the project and encouraged her children to talk about it to friends and family.

Regarding the relationship between *Rafigh* and using the target applications, P3 reported that during this phase P1 had stated several times that "I have to use learning apps, so the mushrooms grow". At the interview, P1 said he believed his use of learning applications impacted the speed with which the mushrooms grew. P2 also described that during the study, if she used more target applications, the more the mushrooms would grow. P2 said she liked using the applications but was not as interested in the mushrooms.

When asked whether *Rafigh* supported communication and collaboration in the home setting, P3 said the project had created opportunities for her to talk to P1 and P2 about nature, technology and their relationship. She believed it was important that the mushrooms were real and not virtual. P3 stated that she believed it is important to have more projects for children that connect technology and nature (i.e., living beings). She said, "it is good to have projects where children grow things". P3 mentioned that previously P1 and P2 had grown flowers with her and they saw the parallels between flowers and mushrooms in the study. She believed interacting with other live beings could help children develop attitudes of caring and empathy.

Finally, when asked about the ambient interaction and the slow feedback latency of *Rafigh*, P3 observed that both children were initially interested in checking the mushrooms and, over time, P2 became less engaged and P1 stayed interested until the end of the study. P3 expressed that perhaps P2 lost interest because the changes in the mushrooms were slow.

Six-month Follow up Interview. In a six-month follow up phone interview, P3 stated that she had several conversations with the child participants about *Rafigh* after the study (i.e., occasionally "at the dinner table"). These conversations were about *Rafigh*, and also about the more general process of research, science and design. P3 mentioned, as a parent, she liked *Rafigh* because it created a sense of responsibility in the children. Additionally, P3 liked the design of the study as the time requirements for her were small and she did not have to fill out long questionnaires. She stated that designing studies such that they require little effort from (already busy) parents is important for successfully recruiting families as study participants.

6.5 User Study 2

6.5.1 Participants

The second case study involved three participants: a 13-year old boy (P4), a 10-year old boy (P5), and one adult participant, the children's mother (P6). P4 has a diagnosis of having severe autism and communication disorders. P5 has a diagnosis of mild autism. I had not met the participants prior to the study. I met them through a mutual acquaintance.

6.5.2 Study Duration

The total duration of this study (not including the pre- and post-interviews) was 17 days: Phase A lasted 7 days and Phase B lasted 10 days.

6.5.3 Results

6.5.3.1 Pre-Study Interviews

Interview 1. The family, whose members participated in case study 2, lives in a small townhouse in a lower middle class neighborhood in the Scarborough neighborhood of Toronto. The family is originally from the Philippines and has immigrated to Canada 5 years ago. P6 is a full time caregiver and takes care of the children at home. She stated that since her children were first diagnosed with autism, she had attended several support groups in the Toronto area that provide information and resources for families with children who are diagnosed with autism. She has also been reading books and online literature about autism and is always curious about learning more about this topic. She stated that there was no occurrence of autism in her family prior to her sons being diagnosed with it. She stated that she was interested in participating in research projects because she believes that the results can be beneficial both in terms of furthering understanding about autism and also by improving the quality of life of people on the autism spectrum and their families. P6 stated that while she believes nothing takes the place of interacting with real people, technology can play a valuable role in helping people with autism practice their social skills.

The pre-study interview also revealed that both child participants, and especially P4, are interested in technology. Both P4 and P5 use an iPod touch and the family computer. Prior to the study, no set limit on screen time was arranged by P6 for P4 and P5. P6 indicated she was interested in the children using as much therapeutic and/or learning applications as possible. P6 has been interested in using tablet applications to help improve P4 and P5's communication and social skills in the past, but had not acted on it prior to the study.

Interview 2. The face-to-face interview was conducted with P6 and revealed that P4 and P5 did not have a pet and did not have experience with caring for a pet or growing plants in the past. The study procedure and the relationship between target applications and their relationship to *Rafigh* was described to P6. P6 later relayed the information to P4 and P5.

Collaborative Session. In the collaborative session, P6 stated that she wanted *Rafigh* to encourage the children to use therapeutic and/or learning tablet applications. She identified a series of target applications shown in Table 6.

Application name	Platform	Category	Skills targeted
Touch and learn: Emotions	iPad	Therapeutic	Facial expression and emotion discernment training
Going Places	iPad	Therapeutic	Social skills training through scenarios
Autism iHelp	iPad	Therapeutic	Expressive vocabulary
Scratch Jr.	iPad	Learning	Programming/story telling
SeeTouchLearn	iPad	Learning	Expressive vocabulary

Table 6. Applications used in case study 2

P6 did not wish to include any non-target applications. Given this condition, I decided to use a ratio value that is bounded by the maximum amount of target application use observed in either of the participants. After enforcing this condition, I calculated the percentage ratio of other values in relation to the upper bound value.

P6 understood and agreed to the data collection procedure as described in section 6.3.1. The choice was made to have P6 collect the data instead of a monitoring program and that the data would be relayed to the researcher during five house visits.

6.5.3.2 Phase A

For the baseline measurement, the percentage ratio of times that the child participants spent on using target applications were R_{P4}^{1-7} = 43%, R_{P5}^{1-7} = 12% and $R_{P4,P5}^{1-7}$ = 27.5% (average for both participants). Table 7 and Figures 18 and 19 show the results from this phase. P4 used more target applications than P5 during this phase.

Study Day	P4 Application use (Minutes)	P5 Application use (Minutes)	P4 Ratio	P5 Ratio	Average Ratio
1	40	20	57%	29%	43%
2	30	0	43%	0%	22%
3	20	20	29%	29%	29%
4	40	10	57%	14%	36%
5	20	0	29%	0%	15%

6	NA	NA	NA	NA	NA
7	30	20	43%	29%	36%

Table 7. Data from Phase A of case study 2, the first column indicates the study day; the second and third columns provide application use times for P4 and P5, respectively; the fourth, fifth and sixth columns provide the percentage ratio of time spent for P4, P5 and P4 and P5 combined, respectively.

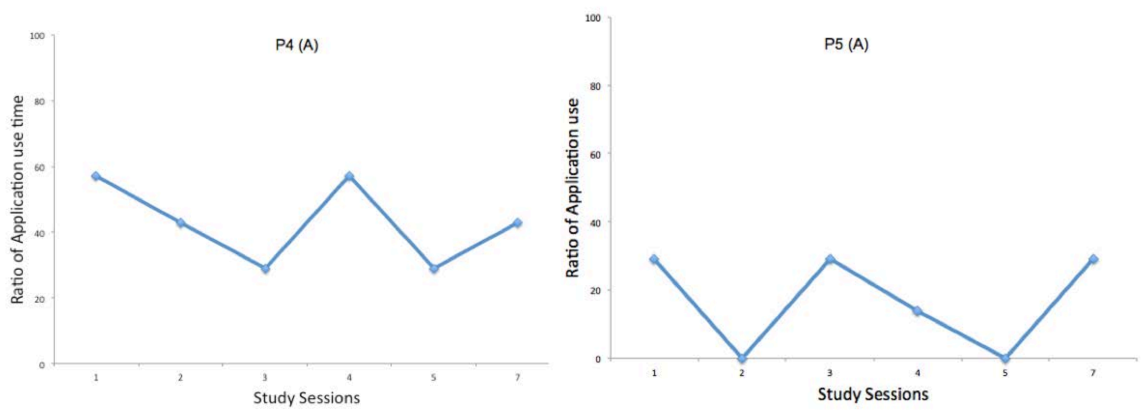

Figure 18. Graphs showing data from Phase A of case study 2. The graph on the left (a) shows data for P4, and the graph on the right (b) shows data for P5. The horizontal axes show the study sessions and the vertical axes show the percentage ratio of target application use.

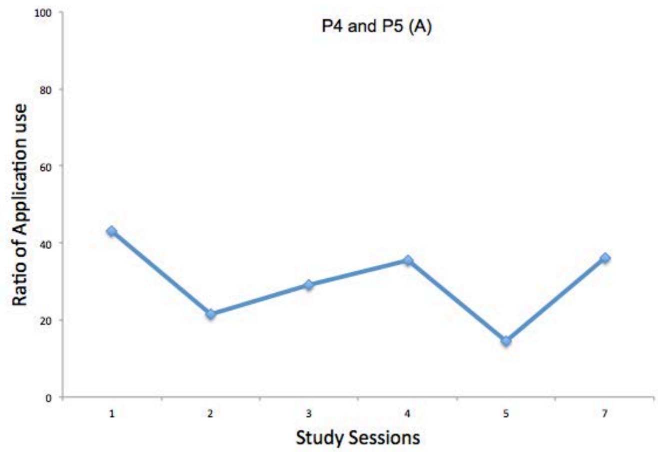

Figure 19. Graph showing data from Phase A of case study 2 for P4 and P5 combined. The horizontal axis shows the study sessions and the vertical axis shows the percentage ratio of target application use.

On one of the days of the study (day 6), P4 and P5 did not use any applications due to other commitments. P6 restricted iPad use for P5 in order for P5 to focus on uncompleted homework. To avoid conflict, neither P5 nor P4 were permitted to use the iPad on that day. This day was treated as an outlier in the data set.

6.5.3.3 Phase B

For the intervention measurement, the percentage ratio of times that the child participants spent on using target applications were R_{P4}^{8-17} = 79%, R_{P5}^{8-17} = 77% and $R_{P4,P5}^{8-17}$ = 78%. Table 8 and Figures 20 and 21 show the data for this phase.

An examination of the data shows that compared to Phase A, there was a marked increase in the average times spent on target applications during the first 8 days of Phase B for both P4 and P5. P5 used slightly more target applications than P4 (R_{P4}^{8-15} = 92%, R_{P5}^{8-15} = 94%). However, during the last two days of the study P5's average time spent on target applications reduced markedly from his average time at the beginning of Phase B (R_{P5}^{16} = 43%). For the last two days, P4's average time reduced from his average time at the beginning of phase B but was still high (R_{P4}^{16} = 58%).

Study Day	P4 Application use (Minutes)	P5 Application use (Minutes)	P4 Ratio	P5 Ratio	Average Ratio
8	60	60	86%	86%	86%
9	70	70	100%*	100%*	100%*
10	60	70	86%	100%*	65%
11	60	60	86%	86%	86%
12	NA	NA	NA	NA	NA
13	NA	NA	NA	NA	NA
14	70	70	100%*	100%*	100%*
15	60	60	86%	86%	86%
16	40	30	58%	43%	35%
17	20	10	29%	14%	15%

Table 8. Data from Phase B of case study 2: the first column indicates the study day; the second and third columns provide application use times for P4 and P5, respectively; the fourth, fifth and sixth columns provide the percentage ratio of time spent for P4, P5 and P4 and P5 combined,

respectively. * In this case study, since the ratio was bounded by the maximum amount of target applications use, the value corresponding to the 100% ratio was forced by the condition observed during the interaction to be 70 minutes/day.

On two days (days 12 and 13) the children did not have access to the iPad. During these days, the family was travelling and decided not to take the tablet. P6 communicated to the children that their not using the target applications during this time would not affect the mushrooms. These days were treated as data outliers.

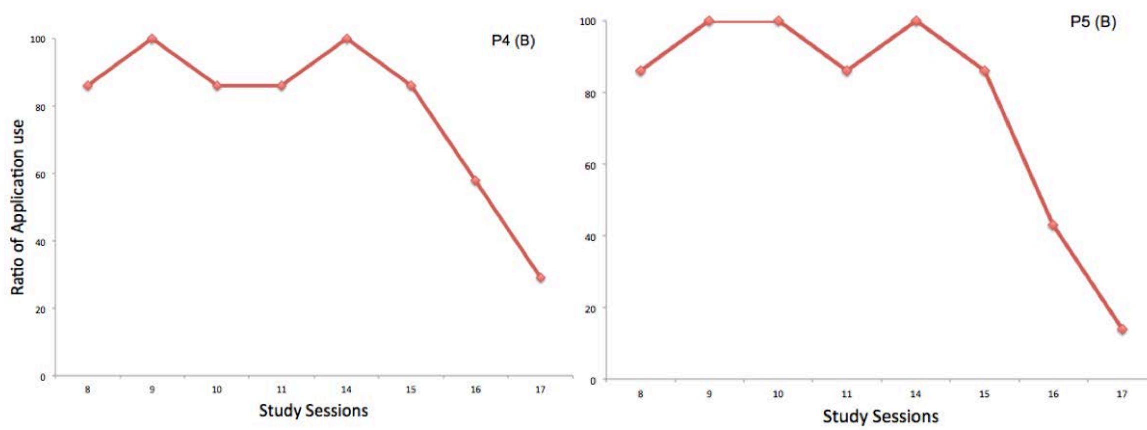

Figure 20. Graphs showing data from Phase B of case study 2. The graph on the left (a) shows data for P4; and the graph on the right (b) shows data for P5. The horizontal axes show the study sessions and the vertical axes show the percentage ratio of target application use.

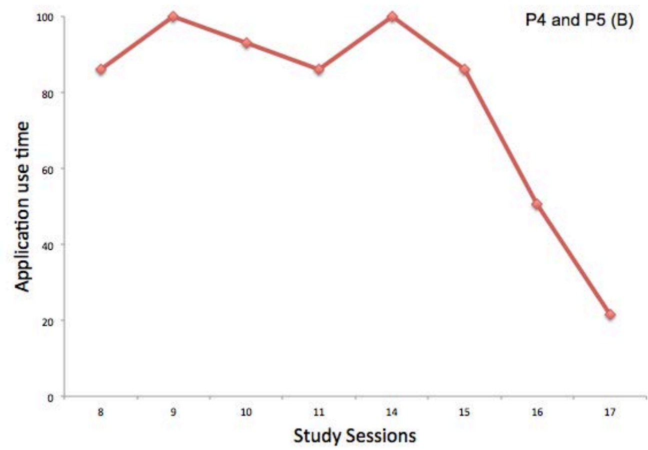

Figure 21. Graph showing data from Phase B of case study 2 for P4 and P5 combined. The horizontal axis shows the study sessions and the vertical axis shows the ratio of target vs. non-target application use.

Once the study was completed, the mushrooms were harvested by P4 and P5 and brought to the children's school to be shown to their peers.

Rafigh Operation. I initialized the mushrooms in *Rafigh*, by soaking it as described in section 5.4.2.1 the day before bringing it to the participant's home. The irrigation level of *Rafigh* changed during the study as per the protocol governing the watering level based on application use for P4 and P5 combined. The irrigation level started the default setting of MEDIUM on day 1 of Phase B (day 8 of the study). It increased to HIGH, in response to a 10% increase in target application use, on day 2 of Phase B (day 9 of the study). It again decreased to

MEDIUM on day 4 of Phase B (day 11 of the study), in response to a 10% decrease in target application use. It increased to HIGH again on day 5 of Phase B (day 14 of the study) in response to a 10% increase in target application use. Finally, it again decreased on day 7 of the study (16) to MEDIUM, in response to a 30% decrease in target application use, and remained MEDIUM until the end of the study (day 17).

6.5.3.4 Post Interviews

In this section, a summary of the data collected during the post-interviews is provided. The full dataset is provided in Appendix D.

Follow up Interview. With respect to the experience of interacting with *Rafigh* and participating in the project, P6 reported that, during Phase B, P4 showed interest in using the applications but did not show interest in *Rafigh* itself. P5, however, was very interested in the mushrooms. P6 stated that on days 16 and 17, P5 noticed that the mushrooms had stopped growing (the growth cycle was finished). He was disappointed by this observation and asked P6 what was wrong and why did the mushrooms did not grow more. P6 described that the growth cycle of the mushrooms was over and it is time to harvest them. P5 did not use the target applications much after this. P4 was undeterred that the growth cycle was over and he was still interested in using the iPad.

During Phase B, P4 and P5 were particularly interested in the Scratch Jr. application and were making short stories and animations using it. Figure 22 shows screenshots from this application.

With respect to whether *Rafigh* created empathy and responsibility in the children, P6 stated that P5 checked the mushrooms everyday and several times asked about how large they are going to grow. P5 was very interested in growing the mushrooms again and had talked about them on many occasions. P5 would check on the mushrooms regularly and expressed many times that he has to use the applications so that the mushrooms would grow, which P6 interpreted as a sign of responsibility towards the mushrooms. At the end of the study, P6 observed that P5 had become invested in the mushrooms' health and was wondering why they do not grow larger. P6 believed that using real mushrooms contributed to P5's interest in *Rafigh* and might have caused feelings of curiosity, empathy and caring in him.

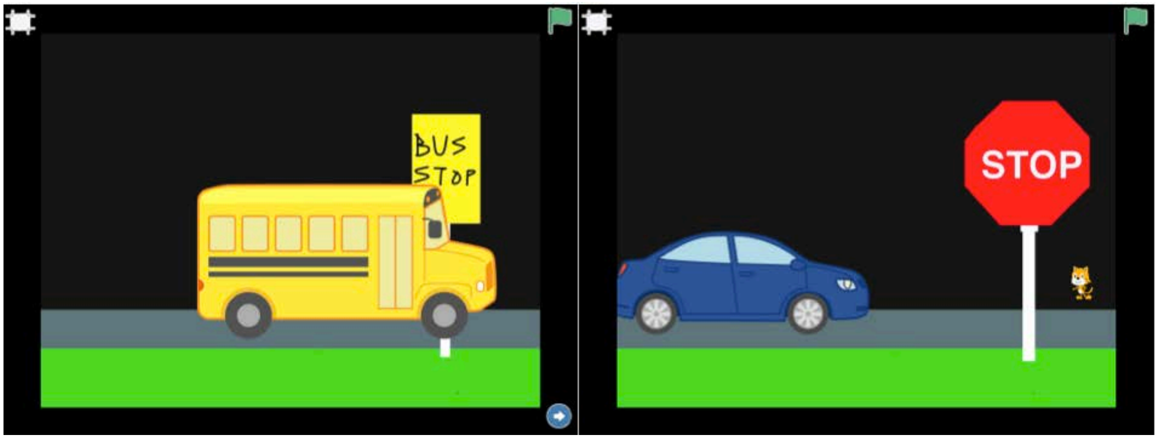

Figure 22. Screenshot of a story created by P4 and P5 using Scratch Jr.

Regarding the relationship between *Rafigh* and using the target applications, P6 reported that P5 had told her several times during this time that he has to use the applications so that the mushrooms would grow; this shows that he grasped the relationship between using the applications and growing the mushrooms. Additionally, he encouraged his brother to use the applications more, in order for the mushrooms to grow.

When asked whether *Rafigh* supported communication and collaboration in the home setting, P6 believed incorporating the mushrooms in the interface had opened up possibilities for dialogue with P5, who had many questions about them. P6 believed the study provided her children with a valuable experience interacting with living beings and learning about life. She believed the project provided possibilities for conversation between her and the children, especially about nature and mushrooms. Throughout the study, she was very supportive of the project and encouraged the child participants to show the mushrooms to friends and family.

Finally, when asked about the ambient interaction and the slow feedback latency of *Rafigh*, P6 stated that the mushrooms had not engaged P4 at any time during the study, whereas P5 was very interested in the mushrooms and was not deterred by their slow feedback latency (at least not until the end of phase B when he realized they will not grow larger and have to be harvested).

Six-Month Follow up Interviews. In a six-month follow up phone interview, P6 stated that P5 still talked about *Rafigh* and has expressed interest in growing mushrooms again. Since the study, P5 has started eating mushrooms, a habit he did not have prior to the study.

6.6 Analysis

The case studies provided answers to the research questions presented in section 6.1. In the following subsections, I present the results of the data analysis that provided the answers.

6.6.1 Target Activities (TAs)

To what degree did using Rafigh influence the behavior of children with respect to their engagement in "target" vs. "non-target" activities?

The TAs consisted of learning and therapeutic activities in the target applications. To answer this question, I looked for significant changes in the dependent variables that reflect the time the children spent on target vs. non-target applications during Phase A and Phase B. All of the quantitative data is provided in Tables 4, 5, 7 and 8 and Figures 23, 24, 25 and 26. Additionally, I examined the qualitative data (presented in 6.3, 6.4 and summarized in Appendix D) for evidence of a connection between the children's use of *Rafigh* and the ratio of target vs. non-target application use times.

Analysis of Quantitative Data

For case study 1, the data shows a post-intervention impact for both P1 and P2 (Figure 23). For P1 the median at Phase A was 50% and at Phase B it was 83% (a difference of 33%) (Figure 23a). The difference between Phase A and Phase B is less pronounced for P2 (a difference of only 13%). A visual analysis of Figure 23b shows that P2 also had a higher level of target application use during Phase B than Phase A. For P2 the median at Phase A was 33% and at Phase B it was 46% (a difference of 13%).

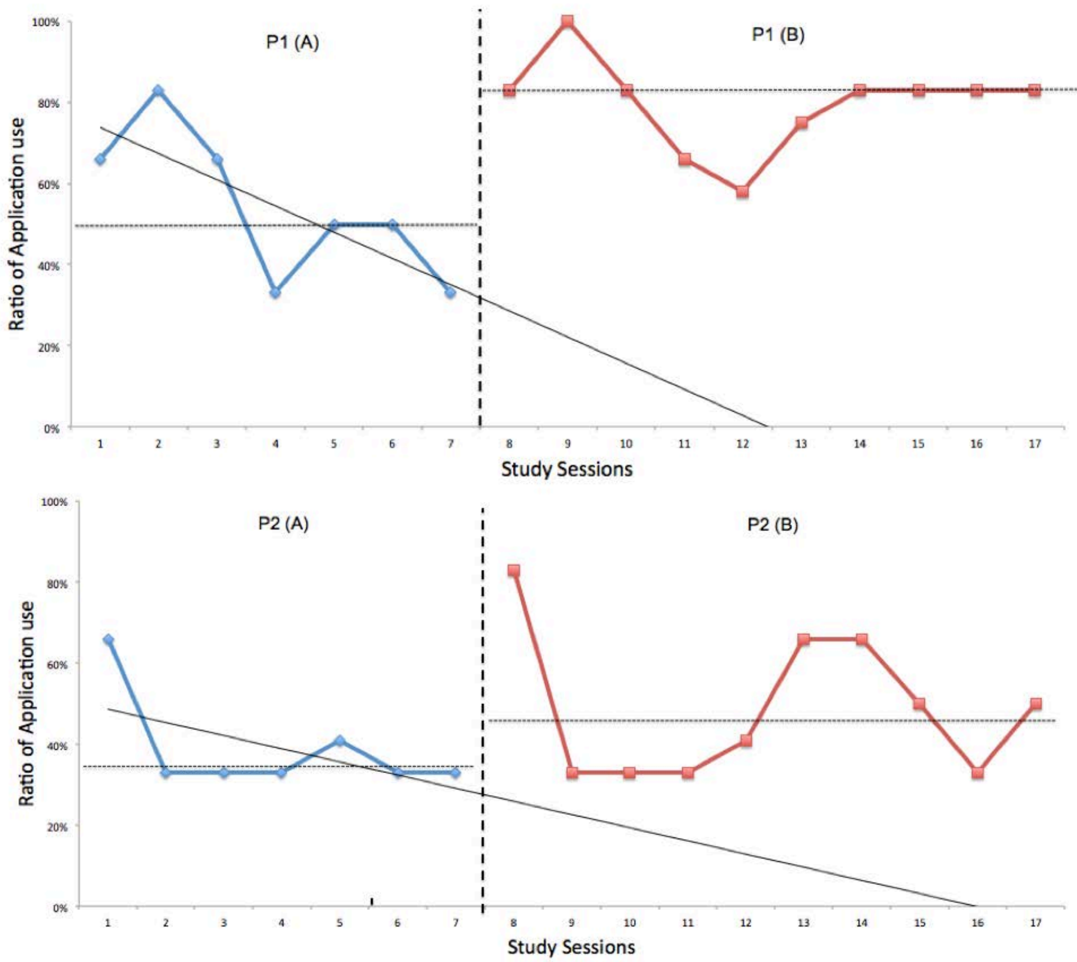

Figure 23. Graphs showing data from case study 1. The graph on the top (a) shows the data for Phases A and B for P1, and the graph on the bottom (b) shows data for Phases A and B for P2. The horizontal axes show the study sessions and the vertical axes show the ratio of target vs. non-

target application use time. In each graph, the trend line for Phase A is drawn and projected onto Phase B. Also, for each phase of each graph a dashed vertical line indicates the median for that phase.

Overall, both P1 and P2 had a higher level of application use during Phase B than Phase A (Figure 24). In Phase A, P1 and P2 had a combined median of 45% and in Phase B, they had a combined median of 66% (with a difference of 21%). I conducted a split-middle method of trend estimation that indicated a significant effect ($p < .005$ in all cases) in Phase B in all three cases (P1, P2 and P1 and P2 combined).

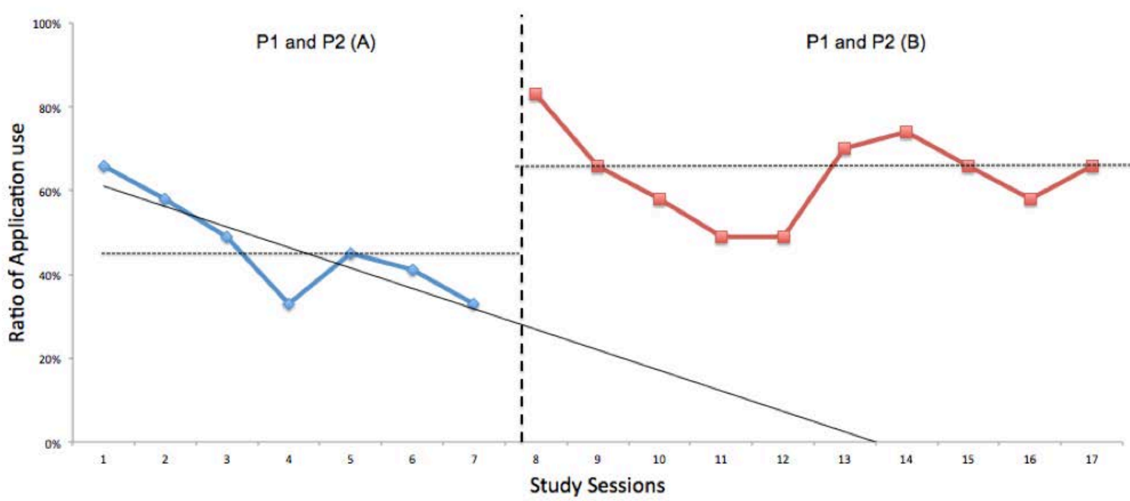

Figure 24. Graph showing data for Phases A and B for both P1 and P2 in case study 1. The horizontal axis shows the study sessions and the vertical axis shows the ratio of target vs. non-target application use. In each graph, the trend line for Phase A is drawn and projected onto

Phase B. Also, for each phase of each graph a dashed vertical line indicates the median for that phase.

For case study 2, the data shows a post-intervention impact for both P4 and P5: a visual analysis of Figure 25a shows that P4 had a higher level of target application use during Phase B than Phase A. For P4 the median at Phase A was 43% and at Phase B it was 86% (a difference of 100%). The difference between Phase A and Phase B is even more dramatic for P5 (a percentage difference of 300%): only 21% in Phase A and 86% in Phase B. Overall, both P4 and P5 had a higher level of target application use during Phase B than Phase A (Figure 25). In Phase A, P4 and P5 had a combined median of 32% and in Phase B, they had a combined median of 86% (with a difference of 166%). Again, I conducted a split-middle method of trend estimation that indicated a significant effect ($p < .005$ in all cases) in Phase B in all three cases (P4, P5 and P4 and P5 combined).

A final observation of the data for case study 2 shows that on the final day of the study (day 17) the target application use times for P5 and, P4 and P5 combined dropped to a level that is very close to the trend line extrapolated from Phase A. Thus, P5 used more target applications when the mushrooms were growing and decreased his application use at the end of the phase when they were fully-grown.

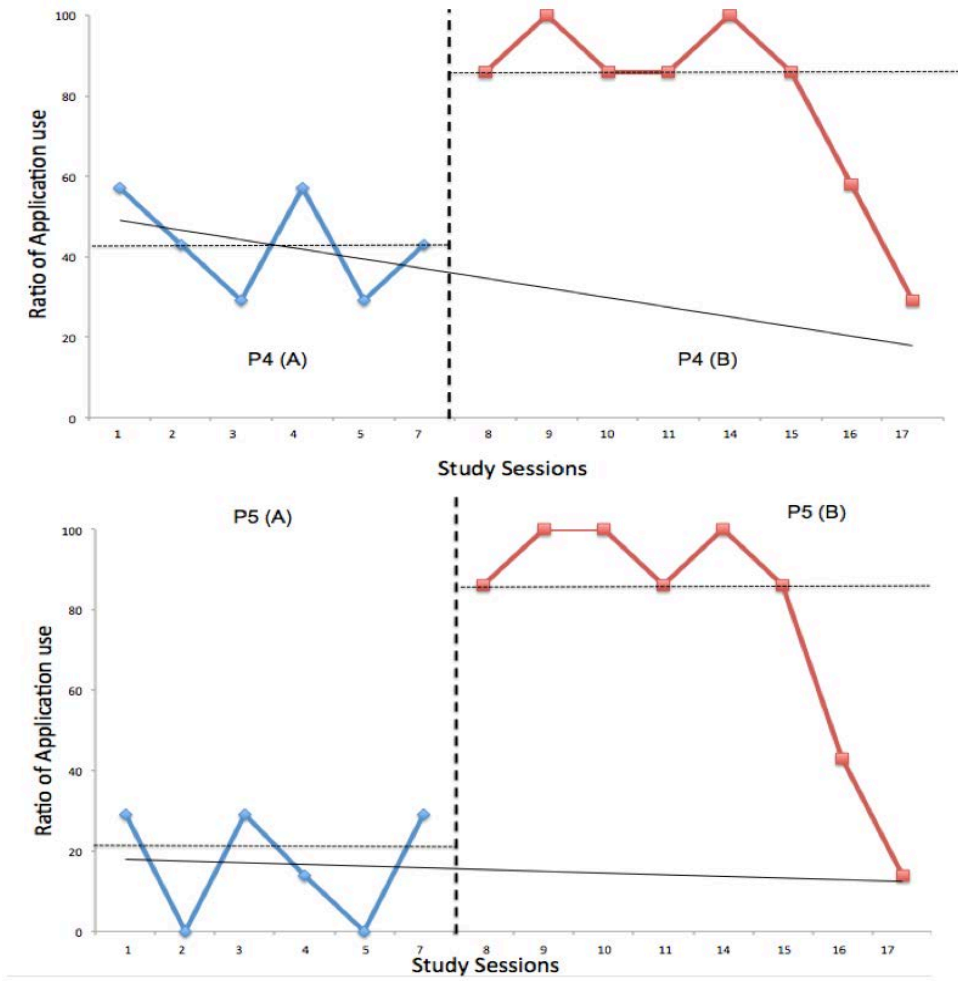

Figure 25. Graphs showing data from case study 2. The graph on the top (a) shows the data for Phases A and B for P4, and the graph on the bottom (b) shows data for Phases A and B for P5. The horizontal axes show the study sessions and the vertical axes show the ratio of target vs. non-target application use. In each graph, the trend line for Phase A is drawn and projected onto

Phase B. Also, for each phase of each graph a dashed vertical line indicates the median for that phase.

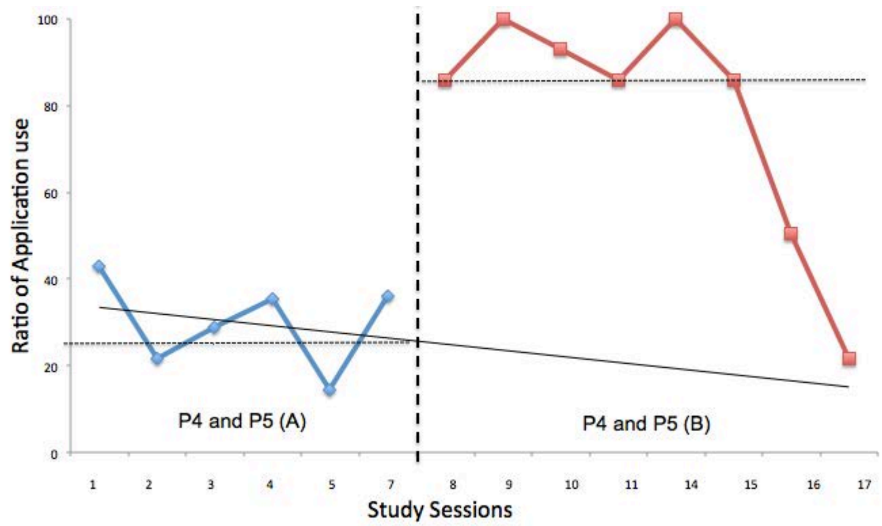

Figure 26. Graph showing data for Phases A and B for both P4 and P5 in case study 2. The horizontal axis shows the study sessions and the vertical axis shows the ratio of target vs. non-target application use. In each graph, the trend line for Phase A is drawn and projected onto Phase B. Also, for each phase of each graph a dashed vertical line indicates the median for that phase.

Thus, the quantitative data shows a significance ($p < .005$ in all cases) increase in the use of target vs. non-target applications for all participants in Phase B when *Rafigh* was introduced.

Analysis of Qualitative Data

The quantitative data showed that the intervention effect of *Rafigh* was stronger for some participants than others. In both studies, one of the child participants (i.e., P1 and P5), but not the other (i.e., P2 and P4), used more target applications as a result of using *Rafigh*. The qualitative data allows for probing for underlying causes of this effect.

In both case studies, when a child took responsibility and recognized his agency in caring for the mushrooms, he stayed engaged with the system until the end. In the first case study, P1 stated several times, that "I have to use learning applications, so the mushrooms grow". Together with P2, he would check the mushrooms first thing in the morning and when arriving from school. He stayed interested until the end of the study. In the second case study, P5 was interested in the mushrooms from the beginning of Phase B to the end of the study. He told P6 several times during this time that he had to use applications so that the mushrooms would grow. He even encouraged his brother to use the target applications more so that the mushrooms would grow more. He checked the mushrooms everyday. Even 6 months after the study, P5 was still interested in the mushrooms and wanted to grow more of them.

In both case studies, when a child did not take an initial interest in the mushrooms, no interest was kindled subsequently. Two of the child participants (i.e., P2 and P4) were not interested in the mushrooms. In case study 1, P2 used more target applications when I first brought *Rafigh* to her home, but started using more non-target applications after a day. When the mushrooms started to become visible, she again started using more target applications and expressed interest. But her behavior again regressed after a short time. The mushrooms' growth rate might have been too slow to capture her attention over a long period of time. In case study 2, P4 started using target applications on the iPad from the beginning of the study but did not express interest in *Rafigh* at any point.

Finally, examining the qualitative data explains an effect observed in case study 2. Recall that the quantitative data from case study 2 showed that on the last day of the study the time measurements for P5 (and P4 and P5 combined) were very close to the trend line extrapolated from Phase A (Figures 25b and 26). At the end of the study, P5 commented that he wanted the mushrooms to continue growing and when his mother told him that they will not grow more and are ready to be harvested he stopped using target applications.

Overall, *Rafigh* was successful at bringing about positive behavior change by motivating one of the two child participants in each case study to use more target vs. non-target applications. This effect was also present in the other two child participants in the case studies but to a much lesser degree.

6.6.2 Means of Engagement

To what extent did dynamics of empathy and responsibility engage the children when using Rafigh and how did using real mushrooms affect these dynamics?

In order to answer this question, I looked for evidence of empathy, caring and responsibility in the children directed towards *Rafigh*.

During Phase B, P1 and P2 referred to the mushrooms as "those guys" or "the little ones". They talked to their siblings, parents and visitors about the mushrooms. These signs indicate that the children might have placed the mushrooms in the role of social partners. During Phase B of the studies, P1, P2 and P5 checked the mushrooms' growth regularly. Both P1 and P5 expressed several times that they "had" to use certain applications so that the mushrooms are cared for. P5 was concerned about the mushrooms' slowing down of growth towards the end of the Phase B and asked P6 about why the mushrooms were not growing more. Towards the end of the studies, P1 and P5 had become increasingly more curious about the mushrooms: P1 asked questions about how the mushrooms grow, how they reproduce and what happens when they die. At the end of both studies, the participants showed signs of pride in having grown the mushrooms in the home and P1, P2 and P5 wanted to (and did) bring the harvested mushrooms to their schools to show them to their teachers and peers. In post-study interviews, P3 stated that the children were interested in the mushrooms' health and wellbeing and P6 mentioned that P5 cared for the mushrooms and was concerned about why they did not grow larger. The cyclical nature of the mushrooms' life, in which they grew, matured and had to be harvested, formed a narrative path. Over time, children and their family members became involved in this narrative and exercised agency by influencing its speed. During the two weeks that the mushrooms were growing, time was available for reflection and dialogue around their mortality. The adult participants (i.e., P3 and P6) believed using "real" as opposed to "virtual" mushrooms as part of the interface was novel and exciting for the children and might have contributed to the creation of a sense of responsibility in them.

Thus, the data shows that using *Rafigh* created responsibility, empathy and caring towards the mushrooms in P1 and P5. Additionally, the data shows (to a lesser degree) that using *Rafigh* created these dynamics in P2. The adult participants expressed that using real mushrooms contributed to the children's interest and excitement and might have been instrumental in generating feelings of empathy, caring and responsibility in them.

6.6.3 Customization

To what extent did children (and their parent(s)/guardian(s)) grasp the relationship between using target applications and caring for the mushrooms?

In order to answer this question, I analyzed the qualitative data for evidence of participant knowledge about the relationship between the use of target applications and the growth of the mushrooms.

In the post-study interview, P1 and P2 correctly described the relationship of their use of target applications and their use of target applications. P6 had observed that P5 had also clearly expressed how the system worked and that he had to collaborate with P4 in order for the mushrooms to grow. Both adult participants (i.e., P3 and P6) successfully described how the system worked. They stated that during phase B, they answered the child participants' questions about the system during conversations in the home.

The evidence suggests that P4 might not have grasped the relationship. P4 did not make any statements that concerned the operation of the system. P6 reported that during phase B, P5 encouraged P4 to use more applications in order for the mushrooms to grow, but P6 did not observe any signs that P4 understood the relationship.

Thus, the analysis shows that the adult participants (i.e., P3 and P6) and three of the child participants (i.e., P1, P2 and P5) grasped the relationship between using target applications and *Rafigh*.

6.6.4 Context of use and Interaction Partners

To what extent did Rafigh support collaboration and communication within the family home context and what characterized these dynamics?

In order to answer this question, I looked for evidence that showed *Rafigh's* presence in the house setting supported communication and collaboration between the child participants and their family members and their friends and school peers.

In each case study, the child participants interacted with each other when using *Rafigh*. In case study 2, P6 reported that P5 encouraged P4 to use more target applications and collaborated with him in creating expressive stories using the applications. In case study 1, the data did not point to direct interaction between P1 and P2. However, both P1 and P2 were initially interested in using more target applications to care for *Rafigh* and, over time, P2 lost interest and P1 stayed interested until the end of the phase. In both case studies, one of the children (i.e., P1 and P5) became engaged with *Rafigh* and demonstrated a visible change in behavior and a visible investment in the mushrooms' wellbeing, whereas their siblings (i.e., P2 and P4) were not as engaged and lost interest early on in the project or only expressed occasional interest. Thus, when collaboratively interacting with *Rafigh*, one of each siblings dominated the interaction.

The evidence also shows that *Rafigh* created communication and collaboration between the adult and child participants. Both parents expressed that having *Rafigh* in the house provided opportunities for conversation around technology, nature and how to interact with both responsibly. Specifically, the adult participants reported that the child participants asked them about how *Rafigh* worked and the wellbeing of the mushrooms. Both parents believed that the children benefitted from the communication and dialogue. While the mushrooms in this domesticated form do not exist in a "natural" setting, they did invoked notions of nature and living beings in nature in the comments provided by parents and children. Thus, *Rafigh* created communication and collaboration between the adult and child participants in each case study.

6.6.5 Technological Instantiation

What was the quality of the children's experience with respect to the slow responsivity of Rafigh?

In order to answer this question, I looked for evidence reflecting the children's experience with respect to the slow responsivity of *Rafigh*.

In each study, one of the child participants (i.e., P1 and P5) showed signs of interest and investment in the mushrooms from the beginning to the end of Phase B, whereas the other two child participants (i.e., P2 and P4) did not. At the end of the study, P1 and P5 wanted to grow mushrooms again. The slow rate of the mushrooms' growth, however, created a challenge in keeping one of the other children, P2, interested. P2 was interested in *Rafigh* at the beginning of Phase B and when changes became visible. However, she did not show signs of interest at other times. In the post-study interview, P3 expressed that perhaps P2 lost interest because the changes were slow.

Another participant, P4, did not become interested in *Rafigh* and was very focused on the tablet applications from the beginning. Thus, the slow rate did not affect his engagement directly. He is the only child participant with severe autism, a condition that might have affected his relationship to the living media.

A possible reason why P1 and P5 became increasingly engaged over time might be the long process during which they saw the changes in the living media system and had time to establish a longer relationship with *Rafigh*. The adult participants (i.e., P3 and P6) confirmed this possibility by stating that P1 and P5 became invested because they believed they were caring for the mushrooms over a long time.

Rafigh communicated information (i.e., through the growth of the mushroom) over long periods of time. Changes in the mushrooms' appearance take hours, as opposed to milliseconds (in the case of commonly used digital displays). Thus, the case studies showed that the slow responsivity of *Rafigh* might have contributed positively to two of the child participants' engagement. However, it might have been too slow to engage one of the child participants.

What was the quality of the children's experience with respect to the ambient interaction it afforded?

In order to answer this question, I looked for evidence reflecting the children's experience with respect to the ambient interaction that *Rafigh* afforded.

The children checked the mushrooms' growth after a long period of time had passed (i.e., after school or in the mornings when they woke up). Both of the adult participants (i.e., P3 and P6) commented that the mushrooms' growth mechanism piqued the children's curiosity. They stated that *Rafigh's* presence in the home provided them with opportunities to describe (to the children) how mushrooms live and grow. In the post-study interviews, both adult participants (i.e., P3 and P6) expressed that participating in the study was a valuable learning experience. P3 said it was good to have projects where children grow things and become familiar with life. Prior to the study, P1 and P2 had grown flowers with P3's help. In both case studies, the adult participants, P3 and P6, were consistently interested in the process and encouraged the children to show *Rafigh* to their friends and family. At the conclusion of the studies, both P3 and P6 agreed to the children's request to bring the harvested mushrooms to their school. Both of the adult participants (i.e., P3 and P6) expressed that having *Rafigh* in their home created many possibilities for conversation and discussion.

These results point to the conclusion that the ambient interaction that *Rafigh* afforded was engaging for the child participants and was perceived as positive by the adult participants. *Rafigh* supported unobtrusive and consistent possibilities for being observed and interacted with by the children: it existed in the family home and, therefore, like a house plant or family garden became a part of the family's physical environment. It shared space with the inhabitants of the houses it was placed in. Once the mushrooms started growing there was no on and off button and they were "just there", creating possibilities for reflection and conversation. This contrasts to digital media that can be paused and turned on and off. *Rafigh* constantly existed in the users' homes, but it did not need to be constantly attended to. Its constant presence meant that attention on it could quickly move from the periphery to the center of focus, slipping back to periphery again as needed. During the study, the children would focus on *Rafigh* after long periods of time when changes were visible, or when they wanted to show it to visitors; at other times, *Rafigh* slid into the background and continued its non-obtrusive existence. The fact that children could observe the changes in the mushrooms whenever they wanted in their house might have contributed to a stronger sense of engagement and investment.

6.7 Discussion

In addition to answering the research questions, the case studies revealed interconnections between the questions. Results from the intervention phase revealed signs of empathy, responsibility and curiosity towards the mushrooms in two of the child participants (i.e., P1 and P5) (Research Question 2). These same participants also displayed pronounced intervention effects in terms of increased target application use (Research Questions 1). These results point to the idea that the dynamics of dynamics of caring, responsibility and curiosity that *Rafigh* brought about in the child participants might have caused their behavior change.

Further interconnections can be observed between the quality of the children's experience with respect to the ambient nature of *Rafigh's* interaction (Research Question 6) and the sense of responsibility and empathy present in the child participants (Research Question 2). Figure 27 shows a sample timeline of *Rafigh's* use in relation to a digital tablet application: while the application was paused whenever it was not used, the lifecycle of the mushrooms connected to *Rafigh* continued. The mushroom colony was alive and, hence, once its growth was activated, it could not be paused (as it would be in a virtual version). The notion of "pausing" a digital activity is common in game design and, indeed many digital activities, where the user is oftentimes given control over when they want to pause gameplay and continue playing from where they left off at a later time[29]. This was impossible with the living media: although the users had control over the speed with which the mushrooms connected to *Rafigh's* interface grew, they could not stop the growth process once it was started[30]. In real life situations, our actions and inactions have implications. We cannot "pause" time in the real world or speed it up or down. Life will go on, whether we like it or not. *Rafigh's* mushrooms were not only similar to life; they were alive! When using *Rafigh* children experienced that both their action and inaction have implications in the real world.

Another interesting connection exists between the ambient nature of *Rafigh's* interaction (Research Question 6) and how it created communication

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[29] This discussion does not include digital activities in which other human agents are involved (e.g., Second Life or other multiplayer online games).

[30] There are mechanisms, such as cryonics, by which biological processes are "paused", in the sense that biological processes are stopped or significantly slowed down (Hughes, 2001); but the application of these processes are still far and few in between and not relevant to Rafigh's design.

between family members (Research Question 4). Since *Rafigh* had a physical form that persisted in the home environment even when the children did not interact with it, it provided time for the children to experience its ambient existence. The results indicated that this quality allowed the children to inspect the mushrooms whenever they wanted during the intervention and created opportunities for dialogue between family members (e.g., at the dinner table).

Results from the case studies showed that using *Rafigh* motivated child participants to use significantly more target applications. These target applications were different in each case study: in the first study, they consisted of learning applications and in the second case study they consisted of both therapeutic and learning applications. In both cases, the adult participants identified target applications that would be specifically beneficial for their children. Choosing the AB case-study design provided the flexibility required without loss of power in answering the research questions.

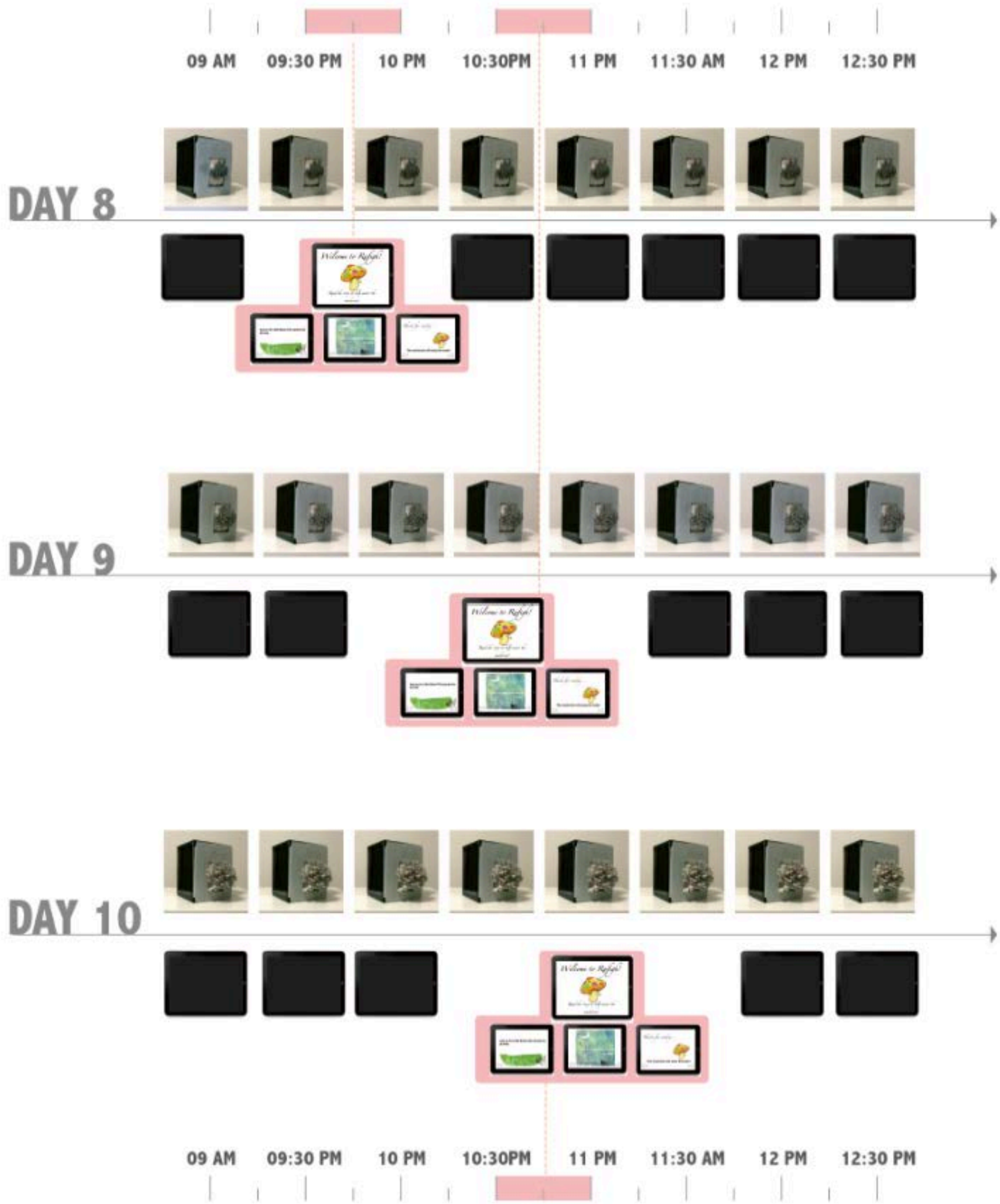

Figure 27. A visualization showing *Rafigh's* usage timeline over 4 hours in 3 days. For each day, the top row shows pictures of Rafigh with the growing mushrooms and the bottom row shows

periods of target application use (with screenshots from an example application) and periods of non-use (symbolized with black boxes).

6.8 Limitations

This research project has several limitations. First, I focused on evaluating motivation and engagement and did not investigate the therapeutic and learning outcomes of using the target applications. Investigating which specific therapeutic and learning outcomes *Rafigh* best supports would help strengthen the selection of target applications.

Second, I chose to focus on the children's interactions with the system as the main phenomenon under study. There are additional opportunities to study the socio-cultural context in which the studies were conducted. More data could be gathered about the social context in which the child participants used the system. In this study, I focused on the child participants and one parent but more interviews with other people who were present during the study could provide more insight into interactions in the home setting. Additionally, in both case studies, the child participants brought the grown mushrooms to their school. Observing the way the child participants presented them to their classmates and teachers might have provided further insights into how they perceived their relationship with *Rafigh* (e.g., if any signs of pride or self-efficacy present).

Third, in case study 2, I focused on data about the children's use of technology in the home setting and did not gather extensive data about the diagnosis of the child participants. Broadening the scope of the gathered data to include more detailed information about their specific diagnosis, possibly by conducting their doctor or special education teacher, would have provided insights into possible ways that this factor might have impacted the quality of their experience when interacting with *Rafigh.*

Finally, the living medium in this research was limited to one type of edible mushroom. I provided my reasons for this choice in section 5.4.2.1. In future, other living mediums (including other kinds of mushrooms) can be incorporated into *Rafigh* and compared with the current mushrooms colony.

6.9 Conclusion

In this chapter, I presented two case studies that I used to investigate a series of research questions about *Rafigh*. This chapter constituted an additional iteration of the Generate, Refine and Reflect phases of the RtD methodology, in which I evaluated prototype 3 with users and refined and reflected on the outcomes of the evaluation. In each of the studies, two children and their mother interacted with *Rafigh* in their home setting for 17 days. In each of the studies, I used *Rafigh* to motivate children to use target intervention activities on tablets.

The case studies answered research questions about using *Rafigh* in the home setting. First, they showed that *Rafigh* was successful to a high degree at engaging child participants in using target activities on tablets, an effect that was more pronounced in the child participants who became invested in the mushrooms' wellbeing. Second, in each of the case studies one of the child participants showed signs of curiosity, empathy and responsibility towards the mushrooms, demonstrating that these dynamics can be successfully used to provide positive reinforcement and motivation during digital interaction. Third, the case studies showed that except for one participant, all the participants grasped the relationship between the mushrooms' growth and using target digital applications on the tablets. Fourth, *Rafigh's* physical design that persisted in the participants' home over a sustained length of time created collaboration and communication between the participants. Finally, *Rafigh* afforded ambient slow interaction that allowed the participants to experience it as part of their physical environment and whenever they wanted to.

The case studies provided many answers but also raised questions to be explored in future research. In the next chapter, I conclude the dissertation and identify promising future directions for this research.

Chapter 7
Conclusion and Future Directions

7.1 Summary of Research

In this dissertation, I addressed the question of how can we develop better computer-based systems that motivate children to use more target applications that support therapeutic and/or learning outcomes. To answer this question, I identified the need for systems motivate and engage children to target implemented activities. I developed and evaluated *Rafigh*, a digital embedded system that uses a living media interface, in the form of a living mushroom colony to incorporate dynamics of empathy and responsibility in order to engage and motivate children to perform target digital activities.

I employed a Research through Design (RtD) methodology (Chapter 2). This methodology provides a systematic framework for conducting Human-Computer Interaction (HCI) research through the design and evaluation of prototypes. Several features of the research project, including its exploratory nature, the existence of multiple confounding factors and its situated and physical characterization, made it suitable for the application of RtD.

In order to inform and situate the project, I conducted a review of research literature on systems that motivate children to use target applications. Specifically, I reviewed previous use of digital living media systems and therapeutic and learning computer applications for children (Chapter 3). The study revealed that incorporating living media in a digital system to motivate children to perform target activities is previously unexplored.

I synthesized observations from the research literature into a design rationale that consisted of a series of design decisions based on six design themes: *Target Activities* (TAs), *Means of Engagement, Customization, Context of Use and Interaction Partners* and *Technological Instantiation* (Chapter 4).

Next, I employed an iterative Participatory Design with Proxies approach to the development, fabrication, and evaluation of three *Rafigh* prototypes (Chapter 5). I worked with Speech Language Pathologists (SLPs), special education teachers, children and their parents/guardians in a process that culminated in a functional *Rafigh* prototype (prototype 3).

I used *Rafigh* (prototype 3) to conduct two case studies in participants' home (Chapter 6). The studies provided answers to the research questions posed in Chapter 5. They showed that (1) *Rafigh* caused the children to spend significantly more time on using target applications during the intervention phase; (2) *Rafigh* was successful in engaging one child participant out of the two in each case study who showed signs of responsibility, empathy and curiosity; (3) all but one of the participants showed that they clearly understood the relationship between using target applications and using *Rafigh*; (4) *Rafigh* created communication and collaboration between the participants; and (5) the slow responsivity of *Rafigh* did not impact the engagement of one child participant out of the two in each case study and might have contributed to their investment in the project. Finally, the ambient presence of *Rafigh* as a physical object allowed users to interact with it freely and as part of their home environment.

7.2 Rafigh and the Four Criteria of Research through Design

In chapter 2, I described four criteria for evaluating Research through Design projects (Zimmerman et al. (2007): *process, invention, relevance and extensibility*. In this section I revisit these criteria and describe the contribution of the project with respect to them.

I believe these results and insights can be useful to several audiences, 1) designers of computer systems and applications (including serious games) for children who want to incorporate empathy and responsibility into interaction; 2) interaction designers and artists who are planning to incorporate living media into their digital systems, installations or art projects; and 3) researchers who work on projects that aim to engage a community of users in situ.

The first criterion, *process*, captures the degree of rigor and detail involved in the development and implementation of the design rationale. In chapter 4, I demonstrated how the design rationale was built up through a research domain synthesis. Additionally, in chapter 5, I demonstrated how experiential knowledge gathered through evaluating each prototype was incorporated into the design of subsequent prototypes. I included details such that *Rafigh's* design could be replicated. Finally, in chapter 6, I described the system evaluation in detail.

The second criterion, *invention,* evaluates the novelty of the design and its potential to inspire future designs. I found no other examples of systems that have explored the potential of using digital living media systems for engaging children with disabilities. Additionally, I could find no previous project that explored incorporating dynamics of empathy and responsibility into computer activities through the use of living media. I situated the design with respect to the current state of research. Through designing and evaluating *Rafigh*, I explored novel research territory and answered several research questions in this area. However, like any innovative project, this research project raised more questions for future research to explore. In this sense *Rafigh* is a novel design and has potential to inspire future researchers and interaction designers.

The third criterion, *relevance*, measures how the prototype can create positive change in the *real* world. While it will take time to determine the true impact of *Rafigh*, I have followed best practices for improving the likelihood of it being relevant to real users. At different phases in the project, I consulted SLPs, teachers, parents, and children in order to incorporate their domain knowledge into the design. Additionally, I conducted the final evaluations in the participants' homes. These choices were made in order to make sure the project is relevant to the real world. I believe that the development of *Rafigh* and systems similar to it, in which empathy and responsibility are incorporated into the interaction, would bring about a desired state of the world. Computers have long helped us become smarter, faster and more efficient. I believe it is time that they help make us more emphatic and compassionate as well. I believe the development of *Rafigh* is a step in this direction.

Finally, the *extensibility* criterion captures the extent to which the project's outcomes can contribute to future research and have an impact. *Rafigh's* true contribution to future research can only be evaluated in time. I certainly believe there is potential for this project to be of use to future research and contribute significantly to the field of computer science and human-computer interaction.

7.3 Future Work

Overall, the user studies demonstrated that *Rafigh* motivated children to engage in target activities. In general, digital living media systems have great potential for implementing and supporting the use of target applications that have benefits for their users including improvements in learning and the acquisition of language skills. Through the design, fabrication and evaluation of *Rafigh,* I showed that it is feasible to create engaging and safe digital living media systems for children that incorporate responsibility, collaboration and empathy, not as side effects, but as the main engaging mechanisms that form the interaction. This dissertation answered several research questions and raised several more for future exploration.

In the current project, target activities were limited to the use of tablet applications. In future *Rafigh* could be used to support more general behavior change. This effect might be harder to measure and study, as it is not limited to interaction with a digital device but is also more general and can be used to motivate users to perform a variety of desired behaviors.

Positive dynamics emerged during the case studies, for example interacting with *Rafigh* encouraged communication between parents and children, and generated an increased sense of responsibility and empathy in the children. These dynamics that were the results of the mushrooms being "real", and the way children were invested in them through a long process. These dynamics also point to the potential of systems that support patience and persistence in children, and engage them in a process rather than just an outcome. Future research could explore digital systems that use living media to reward the exercise of patience and persistence, as well as, caring, empathy and responsibility in their users.

In this project, I focused on evaluating a digital living media system that incorporated real living mushrooms. An interesting direction for future research would compare *Rafigh* with other systems that *simulate* mushroom colonies. Such a system could look like *Rafigh,* but instead of real mushrooms include a virtual, graphical or robotic mushroom colony. The simulated system does not have to be limited to mushrooms, and other life forms such as plants or animals, and even hybrid creatures could be simulated. Additionally, such a simulation could be combined with living mushrooms such that they provide stimulation and motivation from the beginning of the interaction and the children do not have to wait for the mushrooms to become visible before seeing signs of change in the system's interface. User studies could investigate to what extent including these simulated components affects the interaction and, specifically, whether such a system could create similar degrees of empathy and responsibility in children.

In the case studies, an asymmetric dynamic emerged in that one of the siblings dominated caring for the mushrooms, while the other sibling did not express as much interest. While this dynamic is not necessarily negative or undesired, future research can explore different ways to address it. One approach would assign each child their own *Rafigh* to interact with and compare the emerging dynamics with the current study. An interesting research question would be to what extent (if any) this approach affects collaboration and communication between the children and whether it encourages rivalry in terms of whose mushrooms grow faster. Another alternative approach would require the children to perform different kinds of tasks that complement each other in order for the mushrooms to get irrigated. A research project could investigate whether such a scheme creates conflict or more collaboration between the children.

Other future research projects could examine using *Rafigh* in contexts other than the home. For example, case studies could be conducted with *Rafigh* in the school setting where child participants could collaborate with their peers to grow the mushrooms. The results of the case studies could be compared with the current studies. Future research could also examine using *Rafigh* in a clinical context where it is used to support speech language intervention conducted by SLPs. Future research could also examine using *Rafigh* in public spaces such as libraries, where appropriate target applications, such as applications that support learning, are selected to use publicly installed *Rafigh*s. This research project could examine the extent to which displaying *Rafigh* in a public space affects the children's motivation.

Another promising future direction is appropriating *Rafigh* for new collaborative scenarios. For example, a research project could examine what dynamics emerge if parents collaborate with children in order to care for the mushrooms by taking part in mutually beneficial digital activities, such as reading stories together and using educational and/or therapeutic applications. Another research project could study using *Rafigh* in a remote intimacy scenario, where it can be placed at a remote location (e.g., a grandparent's home) and the children can care for it remotely by using intervention-focused applications at home. An interesting research question that could be asked in such a project is to what extent does using *Rafigh* create communication and collaboration between the children and the remote users of *Rafigh*.

Several changes could be made to *Rafigh's* design and their effect on the interaction could be observed in future research projects. By adding more sensors and actuators, the mushrooms' humidity, temperature and light exposure could be detected, allowing for more precise control than the current implementation. Future research can examine whether making these changes actually create perceptible changes in the degree to which the mushrooms' growth could be controlled.

Other changes to the design could provide more information about system state to users. For example, a camera could detect actual changes in the size and/or growth pattern of the mushrooms and communicate these to the user via an additional display or digital application. Another way to make the system more visible to users is to make the irrigation system visible by fabricating the housing for *Rafigh* out of transparent material (e.g., clear acrylic plastic) and using water that is diluted with edible color to irrigate the mushrooms. While the amount of water that needs to be administered to the mushrooms is small, it could be represented by a larger amount of water so that the users view a more dynamic system. A user study could probe whether this approach makes the system more engaging for children and whether it helps with understanding the relationship between *Rafigh* and target applications.

7.4 Concluding Remarks

This research project has shown that digital living media systems have much potential for wide application for motivating children to conduct various beneficial activities. While the focus of the current implementation is on motivating children to use learning and therapeutic applications, in principle, *Rafigh* or variations of it, can be used for many more applications including as a technology to support behavior change and the home component of various formal behavioral or communication interventions. Through describing the design, fabrication and evaluation of *Rafigh*, this document aims to inform and inspire future research in this area.

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Appendix A. A Review of Extant CBSLT Systems

As part of the Define and Discover phases of the RtD methodology employed in this project, I conducted a review of extant CBSLT systems (see section 3.3.2). Results from this review were used to partially inform the design rationale presented in chapter 4. I will present the review in this appendix. Before presenting system reviews, I present an overview of the speech language disorders that they target.

I have categorized the reviewed systems into three categories. First, I will review systems that primarily support intervention for children with disorders affecting speech; these disorders include speech sound disorders, speech delays, hearing disorders and multiple disabilities affecting speech. Next, I will review systems that primarily support children with language disorders affecting pragmatics, thus focusing on the social function of language. These systems are primarily designed for children on the autism spectrum disorder (ASD) and other similar developmental disorders (i.e., Asperger's syndrome). Finally, I will review systems of interest that fall outside these categories. I have summarized the systems in Tables 9 and 10.

Computer-Based Speech Language Therapy Systems for Children

Computer-Based Speech Therapy (or *Training*) systems (CBSTs) refer to computational software (and possibly hardware) systems that are used in support of speech therapy or training (Bälter et al., 2005). I use *Computer-Based Speech Language Therapy* (or *Training*) systems (CBSLTs) to refer to computational systems that are used in support of speech *and* language therapy or training. These systems have been used previously for two main purposes (Eriksson et al., 2005), (i) as tools to facilitate interactive exercises in the absence of Speech Language Pathologists or teachers (Bälter et al., 2005; Vicsi et al., 2000); and (ii) as teaching tools that help the SLP or teacher communicate with the client, during intervention or training, using different feedback mechanisms including speech visualizations and animations of internal speech organs (Bälter et al., 2005; Öster, 1989, 1995, 2003).

CBSLTs are designed to support clinical intervention targeting speech language disorders. *Speech language disorders*, also referred to as *communication disorders*, is a broad umbrella term that encompasses both lower-level *speech disorders,* which affect sound production and articulation, and higher-level *language disorders,* which involve linguistic processing that can also impact speech (ASHA, 1993). For a more detailed description of different speech language disorders, see Appendix A.

Different forms of speech language disorders affect a large number of children. In Canada, according to the *2001 Participation and Activity Limitation Survey* (PALS), 155,000 children aged five to fourteen (or about 4% of all children in that age group) have some form of disability as defined by the WHO (Statistics Canada, 2003). Of this population, 38% (approximately 58,500 children) reported receiving Special Education services, half of which address speech or language difficulties (Statistics Canada, 2008). In the United States, roughly 5% of all children are affected by various speech disorders by the time they enter first grade (NIDCD Health Information, 2010). According to the United States Department of Education, speech, language, and hearing disorders account for 24% of all Special Education students in the United States. This amounts to almost a million and a half individuals (U.S. Department of Education, 2005). Thus, there is a large population of children who could potentially benefit from therapeutic applications that support communication and language skills.

Many clinical intervention programs have been developed to address various speech language disorders in the context of the professional practice of *speech language pathologists* (SLPs). Interventions that target speech language disorders are typically not computer-based and are conducted by SLPs. The use of games and playful exercises during intervention sessions is prevalent. These games and exercises are mostly based on the use of "low-tech" props, such as dolls, pictures and storybooks. These toys are used by the SLP to motivate and to elicit speech, reading or non-verbal communication from the client depending on the disorder being targeted. The SLP provides constructive feedback and instructions based on the client's communication output, addressing the problems causing the specific errors present. During intervention, SLPs provide corrective feedback during face-to-face sessions and the repeated practice is continued at home in their absence. To be effective, these sessions should be followed by hours of practice and exercise, in the form of homework activities, at home or school. The amount of practice and exercise varies according to the client, but can amount to additional hours outside of the time spent in direct contact with the SLP (Johnson & Jacobson, 2007).

Speech language interventions consist of both clinical components that are administered by SLPs in a clinical setting and homework and home practice components that are supervised by parents and caregivers in the home setting, as well as, non-SLP teachers in the classroom environment. Previous research has emphasized the importance of homework and practice in the home that should complement clinical therapy (Pappas et al., 2008; Bowen & Cupples, 2004). The research has stressed the importance of including the child's closest family members (i.e., parents, siblings, guardians and caregivers) as communication partners during home practice. The majority of extant computer-based intervention systems are designed for use in clinics or special education classrooms (see Tables 9 and 10). There is a shortage of computer-based speech language intervention systems specifically designed for use in the home setting and in support of the home practice component of speech language intervention.

Depending on the disorders they target, clinical speech language therapy programs are based on theoretical principles. *Motor learning theory* is a well-studied theory that postulates that the two elements of *repeated practice* and *accurate feedback* are necessary to establish automaticity and skill transfer in untrained situations (Wiepert & Mercer, 2002). This theory is widely applied in speech intervention programs that employ the elicitation and repetition, often through play, of spoken utterances chosen to include problematic sounds, words and sentences (Secord, 2007). Another theory that is widely applied is the *reinforcement theory* that postulates that the use of *positive reinforcement* (i.e., rewards when target behaviors are observed) can bring about improvements in language and communication skills (Whalen & Schreibman, 2003; Ferster, 1964; Fell et al., 2006; Koegel & Koegel, 1987). In this approach, the reward is used as a means of engagement to motivate the child to perform target intervention tasks.

Speech Language Disorders Affecting Children

As mentioned briefly in section 3.3.2, *speech language disorders*, also referred to as *communication disorders* refer to a broad range of both lower-level *speech disorders,* which affect sound production and articulation, and higher-level *language disorders,* which involve linguistic processing that can also impact speech (ASHA, 1993). *Language disorders* consist of *expressive* and *receptive disorders,* affecting active language creation and expression and passive language reception and comprehension, respectively. In addition to verbal language, these disorders also affect reading and writing. Language disorders can affect the *form of language,* the *content of language,* the *function of language* and any combination of them (ASHA, 1993). The form of language consists of a language's *phonology* (i.e., the sound system of the language and the rules that govern the sound combinations), its *morphology* (i.e., the system governing the structure of words and their combinations) and its *syntax* (i.e., the system governing the order and combination of words in a sentence and the relationships between elements in a sentence). The content of language constitutes its *semantics,* the system that rules the meaning of words and sentences. Finally, the function of language concerns its *pragmatics,* the system that combines the other elements in functional and socially appropriate communication.

Speech disorders refer to disorders that affect the production and expression of speech. These can affect the articulation of speech sounds (i.e., *speech sound disorders*), the speech fluency in terms of flow of speech and rate (i.e., *fluency disorder*) and/or the voice quality in terms of abnormal pitch, loudness, resonance, duration and prosody (i.e., *voice disorder*) (ASHA, 1993).

Speech sound disorders (also known as *phonological disorders* and *motor speech disorders*) are lower-level disorders that may be due to physiological, neurological or developmental disorders (Shriberg et al., 2010). They have historically affected the largest subgroup of children with speech or language disorders (Weiner, 1981). Speech errors caused by speech sound disorders are of four types: they either involve the omission of a sound, the addition of extra sounds, the distortion of a sound, or the substitution of one sound with another (Bauman-

Waengler, 2004). These disorders are further categorized into *articulation* (or *phonetic*) *disorders* and *phonemic* (or *phonological*) *disorders. Articulation (*or *phonetic) disorders* are caused by difficulty in the physical production of sound. There are various causes for these disorders, including inadequate learning of motor sequences, impaired motor planning (i.e., *childhood apraxia of speech (*CAS*)*), and other conditions due to damage to the neurological system causing lack of muscle coordination (i.e., *ataxia*) and paralysis or weakness in muscles involved in the generation of speech (i.e., *dysarthria of speech*) (Shriberg et al., 2010). The causes of *phonemic (*or *phonological) disorders* in children are largely unknown but are sometimes hypothesized to be related to cognitive, physical or social factors that result in difficulties with organizing speech sounds into a system of sound contrasts and may include difficulty distinguishing between similar yet different sounds (ASHA, 2015).

Speech language disorders can be *congenital*, defined as “structural or functional anomalies, including metabolic disorders, which are present at the time of birth” (WHO, 2014) or *acquired,* occurring after birth due to disease or accident. For example, *aphasia* is an acquired speech language disorder caused by damage to the brain. *Developmental disorders* are congenital disorders that appear during childhood and slow or impede the natural development of a child (CDC, 2015). For example, *speech delay* is a disorder that causes delays in the achievement of speech milestones in a timeline common in typically developing children. *Autism Spectrum Disorde*r (ASD) is another developmental disorder that can adversely affect communication, language and speech skills. In this context, *intervention* refers to techniques, methods and strategies to support the acquisition of common skills that are impacted by congenital disorders and *rehabilitation* refers to techniques, methods and strategies aimed at the recovery of lost functions due to acquired disorders.

Criteria for Analysis of Extant CBSLT Systems

I analyzed CBSLT systems described in the research literature according to the criteria of *Target User Population, Target Activity, Means of Engagement, Context of Use and Interaction Partners, Technological Instantiation, Customization* and *Efficacy.* In this subsection, I will describe these criteria. In Tables 9 and 10, I categorize extant CBSLT systems based on these criteria[31].

[31] To conserve space, I only show the first 4 dimensions in the tables.

Target User Population: For each system, *target user population* refers to the target population for which the system is designed. In Tables 9 and 10, for each system, I have identified the target user population by the primary disorder(s) that the system addressed. These included speech sound disorders, hearing disorders, dysarthria of speech, speech delays, autism spectrum disorder, Asperger's syndrome, and multiple disabilities.

Target Activities (TAs): Each reviewed system can be categorized by its *target activities* (TAs). TAs are the digital-based activities that implement the speech language intervention protocol that underlies the CBSLT. TAs are clinically based, have clinical targets (speech or language), and outcomes that can be measured clinically. For example, in a CBSLT system that implements an intervention that requires the repetition of a problematic sound or word, the TA can be a prompt to the user to pronounce the sound or word.

As described above, any clinical speech language intervention protocol is based on an underlying theory. Many CBSLTs implement protocols based on motor learning theory that emphasizes the importance of repeated practice and accurate feedback (Wiepert & Mercer, 2002; Engwall, 2006). For these systems, implementing the TA involves providing accurate automatic feedback to the user. The means of engagement (see below) are used to motivate the repeated practice component of the protocol.

Other CBSLTs implement protocols based on reinforcement theory that emphasizes giving positive reinforcements to target behaviors (Whalen & Schreibman, 2003; Ferster, 1964; Fell et al., 2006; Koegel & Koegel, 1987). For these systems, a key requirement is that the system is engaging so that the user interacts with it and produces the targeted behavior, which is then positively reinforced. In these systems, negative or non-positive reinforcement (including lack of positive reinforcement) is provided when TAs are not conducted.

Means of engagement: Each reviewed system can further be categorized by *means of engagement,* which refer to elements in the CBSLT system interface that aim to engage and motivate its users. These means include gamification (including multiplayer games), engaging graphics and audio, virtual agents and the use of narrative and movement.

Many CBSLTs for children are instantiated as serious games. The development of CBSLTs preceded the current zeitgeist of gamification. The terms *gamification* and *serious games* antedated the development of systems that incorporated gaming mechanisms in serious settings and, therefore, the terminology is not prevalent in older research literature. However, the principles can be recognized. In the past, most CBSLT systems designed for children did incorporate gaming mechanisms (such as high scores and levels), as well as, playful elements in their interaction design (see system reviews in Appendix A). Currently, given the success of gamification and its potential for engaging users, most CBSTs include gaming elements in their design.

The use of serious games in rehabilitative CBSLT systems is researched previously, especially with respect to demotivation. Rehabilitation is similar to intervention in that it often involves the performance of repetitive tasks that target specific areas for improvement. A large amount of practice over a long period of time is most often required to achieve results in the therapy. Research has shown that rehabilitation results improve when patients are motivated (Maclean et al., 2002). Demotivation that can lead to resignation is often experienced during rehabilitation due to lack of immediate increase in the user's capabilities (Burke et al., 2009). It has been shown that during rehabilitation sessions, games increased motivation, which led to patients finishing more exercises and achieving better results (Rego et al., 2010). By focusing their attention on the game, patients may forget they are involved in rehabilitation

(Flores et al., 2008). Further, games distract the patient's attention and can aid in pain management (Burke et al., 2009). In the light of these possibilities and potentials many rehabilitative games have been developed in recent years (Alankus et al., 2010; Flores et al., 2008).

There is an interaction between means of engagement and TA. If the TA has its basis in motor learning, then the feedback that is naturally part of the clinical protocol also serves as a device for engagement (whether the task has been completed successfully or not). If the TA has its basis in positive behavior reinforcement then the feedback that is part of that intervention is conditional and is predicated on successful task completion. Thus, engagement can be more difficult for this type of TA.

Context of use and Interaction Partners: For each system, I also identified its *context of use*, by which I mean whether the system was designed for use in a clinical setting, a home setting or a school setting. The context of use affects *interaction partners* that include parents, caregivers and siblings in the home setting, teachers, and peers in the school setting and SLPs in the clinical setting.

Customization: Another criteria on which extant CBSLT systems can be categorized is the extent to which they implement a *particular* clinical protocol, as opposed to providing a framework in which different protocols can be employed. Thus, systems can be categorized based on their *customization*, expressed through the degree of flexibility with respect to the intervention protocol that is implemented.

Technological Instantiation: For each system, *technological instantiation* refers to the primary computational technologies used to implement system functionality. Many different technologies, and combinations thereof, can be used in CBSLT systems. *Automatic speech recognition* (ASR) refers to a series of techniques combining signal processing, statistical modeling, and machine learning to analyze and to interpret human speech typically by deciphering input acoustic signals into phones or other linguistic elements such as syllables, words or phrases (Cohen et al., 2004). *Tangible and embedded interfaces* (TEIs), also known as *physical manipulatives*, *3D manipulatives* or *digital manipulatives* (Manches et al., 2009; Zuckerman et al., 2005), are characterized by electronic microcontrollers, sensors and actuators that are embedded in either existing or newly designed physical objects (Ishii, 2008). *Computer graphics* refers to a large series of techniques to create images and video using computational tools and processes (Shirley et al., 2009). It is widely used to implement interactive applications including entertainment and learning systems. *Virtual social agents* are virtual entities that are able to utilize artificial intelligence to simulate social interaction through interactive actions based on user input (Bernardini et al., 2013). *Interactive tabletops* are computational interfaces in the form of digitally augmented tables that can detect input from multiple users (e.g., gestures, touches, moving of elements on the table) and provide feedback through a shared interactive display usually projected onto the table (Dietz & Leigh, 2001; Piper et al., 2006). Finally, *digital living media systems* (also referred to as *moistmedia* (Ascott, 2007), *hybrid biological-digital systems* (Lamers and van Eck, 2012) or *biological displays* (Fernando et al., 2009) are technologies that comprise of computational systems that incorporate living media such as plants, animals, fungi or other living beings (i.e., microorganisms).

Efficacy: Finally, systems can be categorized based on the degree to which they accomplish what they intend to do. In my review, I looked for descriptions of system evaluation and assessment in order to distinguish systems whose efficacies are measured from systems that are in still in development stages.

Summary of Reviews of CBSLT Systems

I identified a total of 19 CBSLT systems that deliver speech and language interventions (Tables 9 and 10). Of these, 16 focus on speech interventions and 3 focus on language interventions. I present the complete reviews in the following sections. Here, I present a summary of the reviews with respect to the criteria described in the previous section.

Name (Year)	Target User Disorder(s) / Use Context	Technological Instantiation	TAs protocol	Means of Engagement
pOwerball (2005)	ASD School	TEI/Interactive Tabletops	Reinforce. Theory	Multiplayer Game
SIDES (2006)	ASD / Asperger's Syndrome School	Interactive Tabletop	Reinforce. Theory	Multiplayer Game
ECHOES (2011)	ASD School/Home	Virtual reality environment	Reinforce. Theory	Virtual Agent

Table 2. A summary of CBSLT systems that target language disorders. ASD refers to the Autism Disorder Spectrum.

Name (Year)	Target User Disorder(s) / Use Context	Technological Instantiation	TAs protocol	Means of Engagement
ISTRA (1991)	Hearing Disorder/SSD Clinic	ASR/Goodness score	Motor Learning Theory	NA
Stepping Stone Game (1991)	Dysarthria of Speech/ SSD Clinic	ASR/Speech visualization	Motor Learning Theory	Gamification
Bow and Arrow Game (1992)	SSD Clinic	ASR/Speech visualization	Motor Learning Theory	Gamification
Speech Viewer II (1995)	Hearing disorders/ SSD Clinic	ASR/ Comparable waveforms	Motor Learning Theory	NA
Baldi™ (1998)	Hearing disorders/ ASD Clinic	ASR/ Tongue visualization	Motor Learning Theory	Gamification
STAR (2000)	SSD Clinic	ASR/Speech visualization	Motor Learning Theory	Gamification
Box of Tricks (2000)	SSD Clinic	ASR/Speech visualization	Motor Learning Theory	Gamification

Speech Viewer III (2003)	Hearing Disorders Clinic	ASR/ Comparable waveforms	Motor Learning Theory	NA
Visual Maps (2003)	Hearing Disorders Clinic	ASR/Visual maps	Motor Learning Theory	NA
visiBabble (2004)	Speech Delays Home	ASR/Speech visualization	Home Parent	Engaging Graphics
Flappy Voice (2004)	SSD Home	ASR/Speech visualization	Reinforce. Theory	Gamification
ARTUR (2005)	SSD Clinic	ASR/Vocal tract visualization	Motor Learning Theory	Engaging Graphics
E-Scope (2006)	Multiple disabilities/ ASD Clinic/Home	TEI	Reinforce. Theory	Narrative and Movement
VocSyl (2009)	ASD/Speech Delays Clinic/Home	ASR/Speech visualization	Reinforce. Theory	Engaging Graphics
LinguaBytes (2009)	Multiple disabilities/ ASD Clinic/Home	TEI	Reinforce. Theory	Narrative and Movement
Web-Based Intervention (2013)	SSD Clinic/Home	ASR/Web interface	Motor Learning Theory	Audio Prompts

Table 3. A summary of CBSLT systems that target speech language disorders. SSD refers to speech sound disorder and ASD refers to autism spectrum disorder

Target Activities (TAs)

The review revealed that CBSLTs implement a variety of clinical protocols that target both children with speech disorders and children with language disorders. The TAs depended on the target population and the intervention protocol that was implemented. The review revealed that all CBSLTs designed for use in a clinical setting implement TAs based on motor learning theory, emphasizing the production and presentation of accurate feedback (see Figure 28). Most of the CBSLTs that are designed for use in contexts other than the clinic (i.e., home or school), including systems designed for use in *both* home and clinic, are based on reinforcement theory. In these systems, the intervention is based on providing positive feedback when TAs are conducted, keeping the user engaged and motivated to continue the rewarded activities. An exception is the Web-Based Intervention system that is meant to be used at home and allow the clinician to monitor a child's speech exercises remotely (Parnandi et al., 2013). This system is based on a motor learning theory protocol.

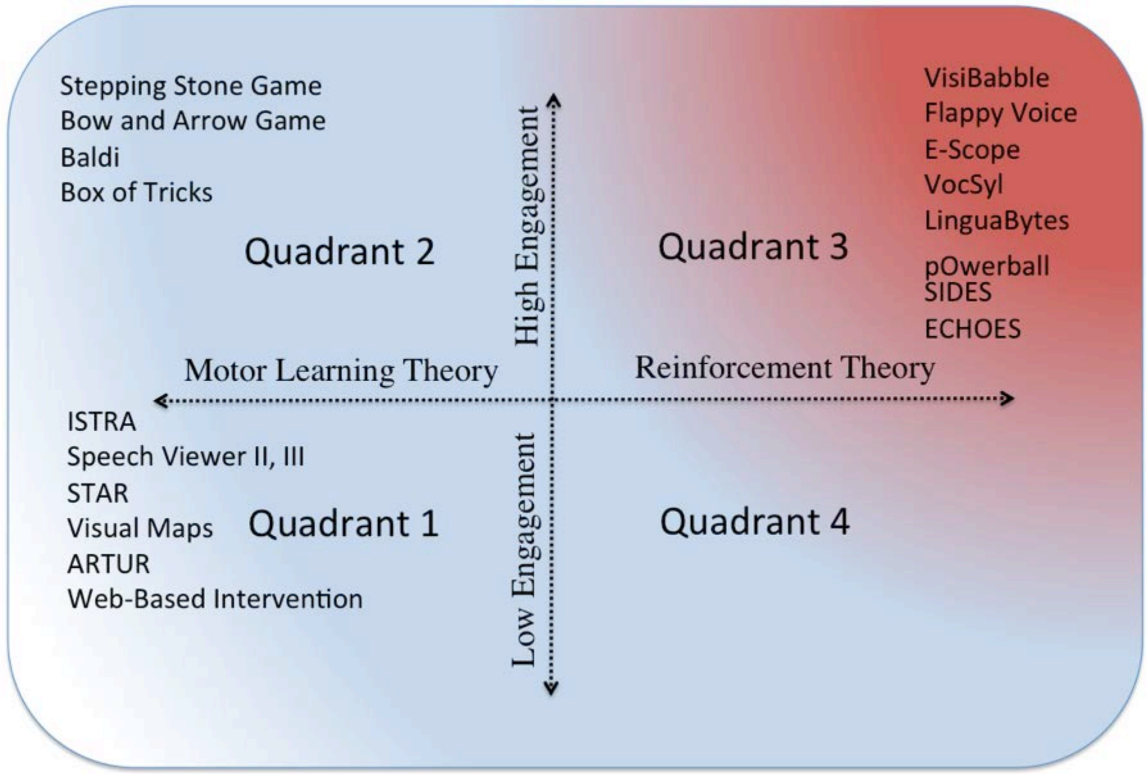

Figure 28. CBSLT systems based on TAs protocol and degree of engagement. The vertical axis represents the degree of engagement of the system and the horizontal axis represents the intervention protocol on which the TAs are based on. Most of the reviewed CBSLT systems designed for use in clinical setting fall into Quadrant 1 (low engagement, TA protocol based on motor learning theory) and Quadrant 2 (high engagement, TA protocol based on motor learning theory). System designed for use in the school and home setting fall in into Quadrant 3 (high engagement, TA protocol based on reinforcement theory). Quadrant 4 is empty, reflecting that CBSLT systems based on reinforcement theory are always designed to have a high degree of engagement. The gradients reflect that degree of engagement is a spectrum that depends on the child's perception. The TAs protocol is designed into the CBSLT system by its developers.

Additionally, all CBSLTs that target language disorders are designed based on protocols based on reinforcement theory. For these systems the key task has been to keep the children interested in TAs that support language, communication and affective skills (Bernardini et al., 2013).

For systems in which the intervention is based on a motor learning theory protocol, providing meaningful and corrective feedback based on input speech is important (Engwall, 2006). CBSLT systems have mainly relied on ASR as an enabling technology. Once input speech is analyzed using ASR, a form of feedback design has been used to provide feedback to users. Thus, automatic feedback has taken the form of comparable waveforms (Speech Viewer II, III), visual maps (Visual Maps), goodness scores (ISTRA), speech visualizations (VocSyl, Flappy Voice, visiBabble, Box of Tricks, STAR, Bow and Arrow Game, Stepping Stone Game), tongue visualization (Baldi™) and vocal tract visualization (ARTUR). For these systems, the provision of meaningful and consistent feedback to children was persistently a key challenge that was not successfully met (Massaro and Light, 2004; Bosseler and Massaro, 2003; Bunnell et al., 2000; Ryalls et al., 1994; Pratt et al., 1993).

Previous research has identified the main cause of this problem as the fact that ASR technology is not mature enough to provide corrective analytic feedback and can only provide evaluative feedback (Hincks, 2002; Menzel et al., 2000). ASR modules are originally developed for recognizing speech rather than evaluating or analyzing speech. By relying on ASR modules to provide detailed corrective feedback, the designers have risked providing the user with confusing and inconsistent feedback. Furthermore, even if the analytic feedback could be derived from ASR-based analysis, the issue of feedback design (i.e., how to translate the results to feedback that is meaningful to children) remains a challenge. Abstract representations such as waveforms and closeness scores were found to be unintuitive for children and have not been helpful in correcting speech. Interestingly, the use of ASR as means of engagement (e.g., in Box of Tricks, VocSyl, visiBabble and Flappy Voice) has been successful in creating engaging interfaces for children and making some systems interactive and responsive (Fell et al., 2006; Hailpern et al., 2012; Vicsi et al., 2000).

The above observations show that it is promising to develop a system that is based on a reinforcement theory protocol, in which the means of engagement (see below) are used to motivate the users to conduct TAs.

Means of Engagement

A variety of techniques are used to implement means of engagement in CBSLTs. These include gamification (i.e., Bow and Arrow Game, Stepping Stone Game, Box of Tricks, Baldi™, STAR, pOwerball, FlappyVoice), engaging graphics (i.e., VocSyl, ARTUR, visiBabble), virtual agents (i.e., ECHOES), narrative and movement (i.e., LinguaBytes, E-Scope), and multiplayer games (i.e., pOwerball, SIDES). Only one project, ECHOES, used interaction with a virtual agent as means of engagement. The project focused on using the agent as a communication partner with whom the child could practice turn taking and affective skills (e.g., body gesture recognition) and explore a virtual space and did not study the potential of using the agent to generate responsibility or empathy in the child (Bernardini et al., 2013). Thus, the dynamics of empathy and responsibility are not explored previously as means of engagement in this domain.

Customization

In all of the reviewed CBSLT systems, the TAs and means of engagement were *tightly coupled*, in the sense that there was a close relationship between them. For each system, both components were developed together and it was not possible to switch the intervention module with other modules. This meant that each system was useful for supporting a specific intervention or a few similar interventions and could not support different interventions at different times.

Context of Use

The majority of extant CBSLT systems are designed for use in clinics or special education classrooms (see Tables 9 and 10). A small number of systems can be used in both clinical and home settings (i.e., visiBabble, VocSyl, Flappy Voice, Web-Based Intervention).

Technological Instantiation

The review revealed a variety of means of engagement employed in extant CBSLTs. A small number of recent CBSLTs have used tangible and embedded systems (i.e., E-Scope, pOwerball, LinguaBytes). Most of the systems are developed for use on a desktop or tablet computer. Currently no CBSLT systems exist that combine living and digital media in a CBSLT system for children.

In the reviewed systems, technology is often used to implement a means of engagement (such as a gamification component) to motivate the children to complete (and repeat) TAs. For example, in the pOwerball system, a tabletop game is used to encourage children to communicate and collaborate with each other (Brederode et al., 2005). There is strong evidence that documents that using technology to engage children is promising. The qualitative feedback from the children (when available) was overwhelmingly positive for the reviewed systems (i.e., pOwerball, SIDES, ECHOES, LinguaBytes, VocSyl), providing evidence to support the hypothesis that computer-based games are appealing to children and will provide a useful tool to support and supplement learning and rehabilitation. When the children articulated negative responses, they typically identified confusing or inconsistent feedback as a source of frustration (i.e., ARTUR, Baldi™). Thus, CBSLTs can engage children but the feedback has to be designed carefully to avoid creating confusion or inconsistency.

Efficacy

Regarding the efficacy of the reviewed systems, with a few notable exceptions (i.e., ECHOES, Baldi**™**, VocSyl) most CBSLTs described in the research literature are prototypes that are not fully developed or evaluated. Thus, it is difficult to determine their efficacy and whether they actually accomplish in practice what they are intended to do. It is important to evaluate CBSLTs with real users, in order to both find out the extent of their efficacy and also, to find out effects other than the intended results they might bring about.

Review of CBSLTs Targeting Children with Speech Disorders

Many language learning and practice applications have been developed in recent years for smartphones and tablets. Many of these applications are digital versions of flashcards and pictures to help SLPs in intervention (e.g., Phonics Studio[32]). A few of these applications record speech and provide data gathering (e.g., Articulate It![33]). Some other applications are developed specifically to implement speech intervention protocols. Examples include Apraxiaville[34], ArtikPix[35], Speech With Milo[36] and Pocket SLP[37]. While studies to evaluate their usability and efficacy are yet to be conducted, the potential benefits of these applications for speech training and intervention are clear. Other computational language intervention systems, such as Earobics (Cognitive Concepts, 2000), Laureate Learning Software (Semel, 2000; Wilson & Fox, 1997), and FastForword

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[32] https://itunes.apple.com/ca/app/phonics-studio/id547795266?mt=8

[33] https://itunes.apple.com/ca/app/articulate-it!-pro/id391296844?mt=8

[34] https://itunes.apple.com/ca/app/apraxia-ville/id611587011?mt=8

[35] https://itunes.apple.com/ca/app/artikpix-full/id356720379?mt=8

[36] http://www.speechwithmilo.com

[37] http://pocketslp.com

(Tallal et al., 1996), focus on listening, reading and spelling skills. They allow SLPs to design exercises to be completed in their absence. Using appealing visual and audio features, as well as basic gaming elements such as rewards and scorekeeping, the exercises motivate children to interact with the computer and practice their speech. These systems also create activity logs and reports automatically, which allow the SLP to assess the clients' activities in their absence. Here, I will limit my review to CBSLTs that focus on speech intervention and have at least one peer-reviewed published description or evaluation.

Many of the reviewed systems use *automatic speech recognition* (ASR) to provide automatic feedback. ASR refers to a series of techniques combining signal processing, statistical modeling, and machine learning to analyze and to interpret human speech typically by deciphering input acoustic signals into phones or other linguistic elements such as syllables, words or phrases (Cohen et al., 2004).

Early Prototype Systems

Bunnell et al. (2000) described a computer system designed to support speech intervention for children with speech sound disorders. The *Speech Training,* *Assessment, and Remediation* (STAR) system is designed to engage children in a role-playing game in which children have to communicate to "aliens" by correctly pronouncing words that usually contain sounds prone to speech errors. In the presented study, the system was supported by an ASR module that was designed to distinguish between the segments /r/ and /w/. For the children population under study these sounds often caused substitution errors. In a study, the accuracy of the ASR module for distinguishing substitution errors occurring in children's speech was measured. When compared with results from human judges, the ASR module could reliably recognize substitution errors. However, it also produced many false positives (i.e., incorrectly categorized correctly articulated examples as errors).

Kewley-Port et al. (1991) presented another system, the *Indiana Speech Training Aid* (ISTRA), in which recorded templates of the child's best production were collected and then used as standards against which to measure the acceptability of new utterances. The researchers conjectured that recognition error rates as high as 20%, a rate within the capabilities of a small vocabulary speaker-dependent system, would be acceptable for articulation training. The feedback provided by the system consisted of a unidimensional goodness score, derived from a comparison of the acoustic representations of input speech and previously stored ones. The system was designed for use in conjunction with SLP-led speech intervention. In pilot studies with two adult participants with hearing disorders and one child with speech sound disorder, it was found that ISTRA could successfully support intervention. However, while the system could be used independently, the SLP had to work closely with the participants in setting up the exercises and interpreting the automatic feedback. With the child participant, ISTRA was used only to support speech drill repetition and the tasks of diagnosis, design of treatment programs, and articulation exercises were performed by the SLP. The system was promising in supporting speech drills and improvements in the speech of both the adult and child participants were noted by human jurors. However, it is difficult to say how much of the improvements were due to the use of the CBSLT and how much to the face-to-face intervention with the SLP. Training of the ASR module was required for each client. The system could not be used with target words and phrases that consisted of segments not producible by the user unless approximations were developed through speech intervention prior to system use.

Box of Tricks

Vicsi et al. (2000) developed a speech intervention system, *Box of Tricks,* to train for vowels and also correct misarticulated fricative sounds. Box of Tricks was designed for use by children with hearing disorders and used ASR to detect and to provide feedback about speech errors. The goal of Box of Tricks was to teach children to modify their speech on the basis of visualizations of their speech signals. Picture-like images of energy, changing in time, fundamental frequency, voiced or unvoiced detection, intonation, spectrum, spectrogram (cochleogram) and spectrogram differences were used for the visualization. A sample screen shot of the program is shown in Figure 29. Box of Tricks was originally devised to support Hungarian, but has subsequently been expanded to also support English, Swedish and Slovenian.

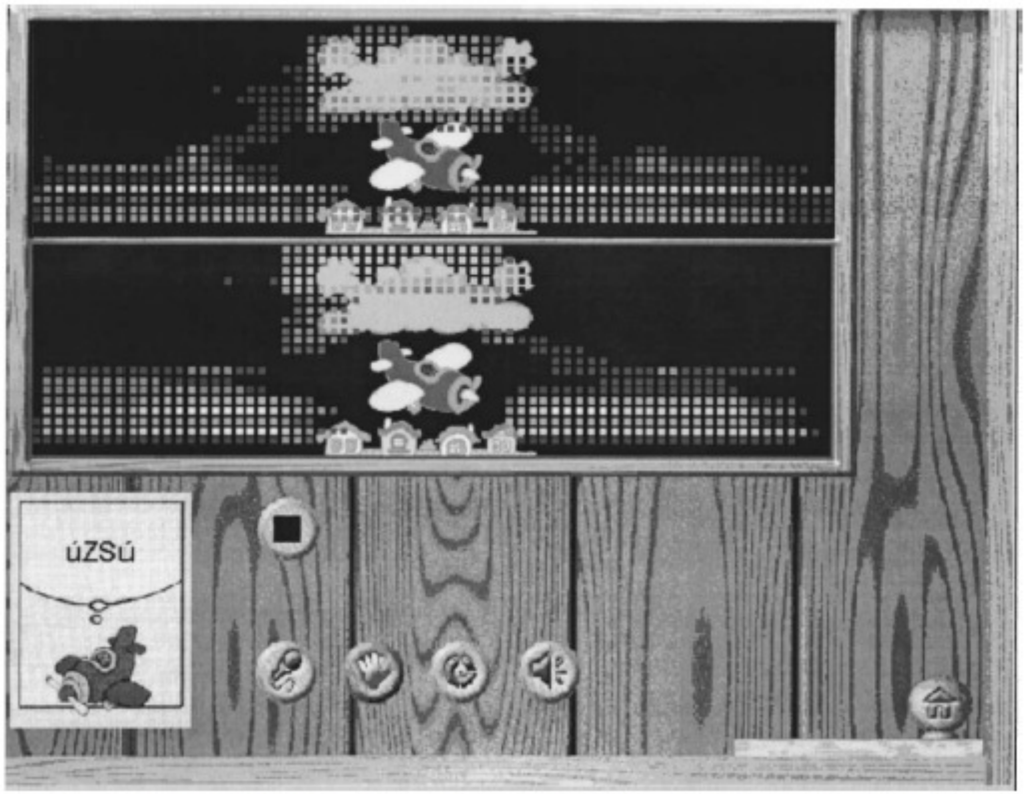

Figure 29. Visual representation of a reference and an input articulation spectrogram (Vicsi et al., 2000)

For the visualizations, a filter was developed and applied that produces a representation based on inner ear processing. The researchers hypothesized that the visualization generated by this filter would be a more intuitive representation of speech as interpreted by humans. The representation of the acoustic signal produced by input articulation was shown in alignment with a representation of a speech signal representing a target articulation. Parts of the representation reflected more important features of the speech, such as cues for different phonemes; amusing background pictures were used to draw the children's attention to these parts.

Box of Tricks did not provide instruction to the children about how to correct their speech, however. Users could see that the feedback indicates that there was something different in the input speech from the desired speech, but it was not clear how this difference could be decreased without corrective instructions.

As a component of this work, Vicsi et al. (2000) proposed the *average spectrum distance* (ASD) as a metric that indicates how close an input articulation is to a target articulation. They hypothesized that this metric corresponds more to the human evaluation of speech. ASD is calculated as the distance of the spectrum components of an input articulation from the averaged target examples. In order to derive the parameters for this metric, a study was conducted that involved collecting human speech samples, followed by human judge evaluations. The scores were then correlated with automatically generated scores in order to find out whether input articulations could be reliability categorized. The researchers found that ASD correlated well with results from the human judges. The researchers claimed that this approach provides meaningful feedback to children and allows them to use the system by themselves. However, no studies were conducted to measure how useful the representations were for children and how successful the system could be in supporting the reaching of clinical goals.

Speech Viewer II* and *III

A commercial speech therapy system, *Speech Viewer II,* was developed by IBM to help adults with speech disorders improve their speech (Öster, 1995). Similar to the systems described above, *Speech Viewer,* works by prompting the user for a specific word or phrase. Feedback about each articulation is presented as waveform representations of the speech signals, shown along a target waveform representing a pre-recorded sample of correctly articulated speech. This form of feedback is referred to as *comparable waveforms* (Neri et al., 2003). The user is then to use this feedback (with support from an SLP) to improve their speech. Figure 30 shows an example of the feedback in the form of waveform visualization provided in response to a user's input speech.

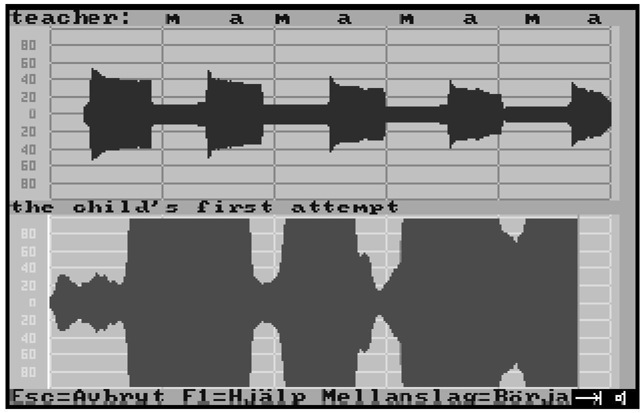

Figure 30. Speech Viewer II displays loudness as produced by the therapist (upper wave) and the client (lower wave) (Öster, 1995)

Several studies that examined the potential of the system for speech intervention for children with hearing disorders reported mixed results. Two studies have shown that it does not work well for use by children with hearing disorders. The first study showed that the program did not have any advantages over traditional speech intervention for vowel training for children with profound hearing disorders (Ryalls et al., 1994). The second study examined the vowel accuracy feedback provided by the system for children with hearing disorders and showed that using the system produced modest gains but exhibited inaccuracies and inconsistencies in feedback (Pratt et al., 1993).

The use of Speech Viewer II's visualizations was unsuccessful for improving pronunciation in children, specifically for correcting speech errors caused by speech sound disorders. However, the system has been promising when used to improve prosodic features of speech for children with hearing disorders. Öster (1989) conducted a study with two deaf children who were trained using the program for ten minutes twice weekly over an eight week period. For each child a different skill was targeted. The first child, a fifteen-year-old boy had difficulty producing durational contrast between phonologically long and short vowels. The second child, a thirteen-year-old girl, had difficulties producing voicing contrasts between voiced and voiceless velar stops. Both children were reported to have demonstrated improvements in the areas targeted after using the system. Öster (1995) also conducted a study with a five-year-old deaf boy who had difficulty controlling the loudness and pitch of his speech. While detailed information about the amount of training, methodology and the results of the intervention was not provided, the researcher claimed that using the program and specifically its graphical interface allowed the SLP to communicate better with the child, resulting in improved loudness and pitch.

In another study with three participants with dysarthria of speech (two adults and one child), Thomas-Stonell et al. (1991a) examined the use of Speech Viewer for vowel production training and voice timing training. She also examined the use of *the Stepping Stone Game,* a similar CBSLT system, in support of speech rate training. The Stepping Stone Game uses an ASR module to map sounds in an input sentence to a gamified graphical representation. Sounds and pauses in a target sentence input by a clinician are mapped to stepping-stones leading to an island (Thomas-Stonell et al., 1991b). To get to the island, the child user has to time their speech such that pauses correspond to the ones in the target sentence (i.e., they "fall on the stepping stones"). Depending on intervention goals, the program can be used to encourage the child to increase or decrease their speech rate.

The participants took part in 24-36 sessions, each lasting 45 minutes. Significant improvements in voice timing, speech rate, and vowel accuracy were observed for all three participants (Thomas-Stonell et al., 1991a). While a clinician was present during the sessions, their role in clarifying feedback and customizing exercises was not discussed. Also, qualitative feedback from participants on engagement or usefulness of feedback from the CBSLTs was not provided.

A new version of Speech Viewer, *Speech Viewer III,* has been developed that consists of a set of 13 clinical modules that include voice, loudness and articulation exercises. Clendon et al. (2003) conducted a study with Speech Viewer III with five children (between 10 and 15 years old) with hearing disorders who had recently received cochlear implants, electronic medical implants that simulate the function of the inner ear. Twice a week, the children received intervention sessions (each lasting 30 minutes) from an SLP using Speech Viewer III and Earobics over two four month periods. The researchers aimed to investigate the efficacy of Speech Viewer III for supporting speech production and Earobics for improving phonological awareness. Among other significant gains in various speech comprehension skills, such as syllabic and phonemic awareness and receptive language, the researchers found significant gains in speech production as measured by the percentage of correct consonants (PCC) (Clendon et al., 2003). The researchers observed that a key consideration during intervention was to keep the children motivated, which was achieved in part by giving them partial control over what exercises they wanted to do in each session. Additionally, they observed that significant input from the SLP with respect to clarification of computer generated feedback and providing of corrective feedback was needed for the interaction to be effective.

Neri et al. (2003) have identified a major problem with providing comparable waveforms to the user. They acknowledge that showing a target and input waveform side-by-side can motivate the user to try to emulate the target waveform by modifying their speech. However, this approach does not necessarily lead to the correction of speech errors and might be misleading. Two articulations might be correct and contain the same phonetic content but still have waveforms that are very different from each other. Neri et al. (2003) asserted that even a trained phonetician cannot extract information needed to correct articulation from this form of feedback, let alone a user that does not have any training in interpreting it.

The above studies have shown, despite the difficulty of interpreting feedback from Speech Viewer without help from SLPs, children are interested in visualizations as engaging stimuli. In a study with ten non-verbal children with autism, Bernard-Opitz et al. (1999) used Speech Viewer in ten sessions (each lasting five minutes) to elicit vocal imitations. They found sessions in which

Speech Viewer was used were significantly more successful in motivating vocal imitations than face-to-face sessions where parents and caregivers used non-digital toys to motivate the children. This approach (similar to *VocSyl* reviewed below) demonstrates the strength and potential of interactive computer applications in engaging and motivating children to conduct repetitive tasks.

Thomas-Stonell et al. (1992) built a CBSLT system, the *Bow and Arrow Game* that aimed at providing feedback for stop consonants for children. The program was designed to be compatible with Speech Viewer and consisted of a custom ASR module developed to distinguish between phonemes that are commonly substituted by each other by people with speech sound disorders. Feedback was provided in the form of a game interface in which a player was shooting arrows at a target. To hit the target, the child had to match the speech sample produced by the clinician by his or her own input speech. The research focused on testing the ASR module with five adults with no speech disorders and found that substitution errors could be classified with high accuracy. In the absence of a user study with child participants, it is difficult to know how engaging or effective is the feedback.

CBSTs using visual maps

Öster et al. (2003) conducted initial experiments with a system that produced custom visualizations, *visual maps*, for training Swedish *sibilant fricatives*, fricatives with higher-frequency and acoustic energy than non-sibilant fricatives, for users with hearing disorders. *Visual maps* consist of diagrams in which the acoustic difference between previously selected Swedish sibilants in terms of frequency range is represented by the vertical axis. The front and back vowels are placed along the horizontal axis to represent a visual path for a combination. Fixed points placed along the axis are used to compare input speech with pre-recorded (i.e., trained) speech models. Figure 30 shows an example of a visual map. The visual maps provide a different way to provide the user with a visual representation of his or her speech in relation to the visualization of target speech. The system was designed to supplement speech intervention in the presence of a SLP. The researchers hypothesized that having this form of feedback would help increase the frequency of correct pronunciations.

Initial maps were created for three sibilant fricatives, /s/, /C/ and /S/, using the speech of a girl with normal hearing. The subject was instructed to pronounce consonant-vowel (CV) combinations, where the consonant was a sibilant fricative /s/, /C/ and /S/ and the vowel was either /i/ or /u/. The acoustic data files were manually segmented, labeled and subjected to spectral analysis before being input to a multilayer perceptron that outputs the positions of data points on the feedback map. Each point corresponds to a fricative and is placed with respect to their frequency range. Figure 31 shows an instance of the map.

The speech of three children with severe hearing disorders was recorded and mapped against automatically generated maps. The speech samples were of the children pronouncing the fricatives, using consonant-vowel-consonant (CVC) combinations where the first and final consonants were each one of the sibilant fricatives mentioned before and the vowel was either /i/ or /u/. It was found that the automatically created visualizations corresponded well with input speech as interpreted by human judges.

This system showed that it is possible to create visualizations that correspond with non-standard input speech. However, it is not clear how useful this approach is for children. The input speech that is to be automatically analyzed by the ASR module is restricted to CVC combinations rather than words, and the visualizations are shown in terms of time and frequency, an unintuitive approach for children. At the time of the study, the project was in initial development phase and no further user studies have been conducted since (Öster et al., 2003).

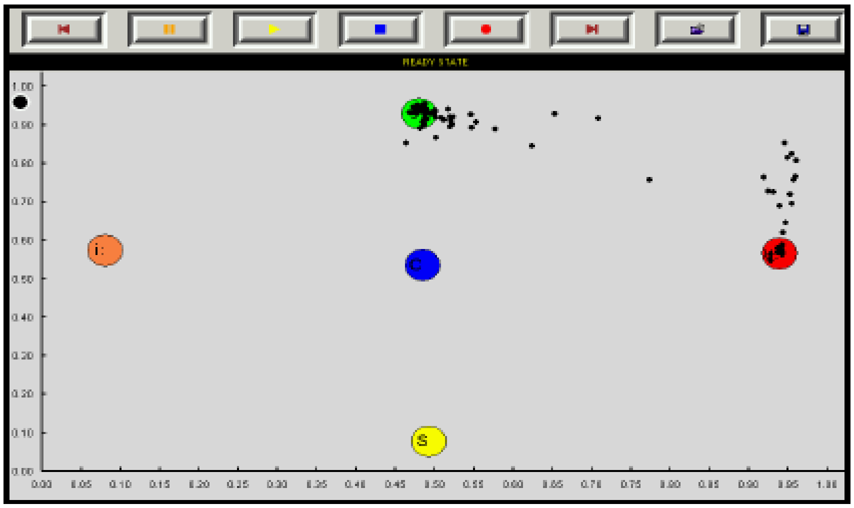

Figure 31. Map interface where input speech is represented by points (black dots) that are placed relative to trained data (fixed color circles) for Swedish sibilant fricatives (Öster et al., 2003)

Baldi™

Cohen et al. (1998) developed *Baldi*™, a computer-animated 3D talking head that can simulate tongue movements inside the mouth to match natural or synthesized speech. Baldi™'s skin can be made transparent, so that the inner position of the tongue relative to other organs is visible during speech. Additionally, supplemental visualizations such as vocal cord vibration and turbulent airflow during speech can also be made visible if needed. Baldi™ is designed for use in support of speech intervention in a clinical setting where the SLP can use the automatically generated animation to demonstrate tongue movements required to articulate a word correctly to children. Essentially Baldi**™** is a tool to show the movement of internal speech organs and specifically the tongue to children.

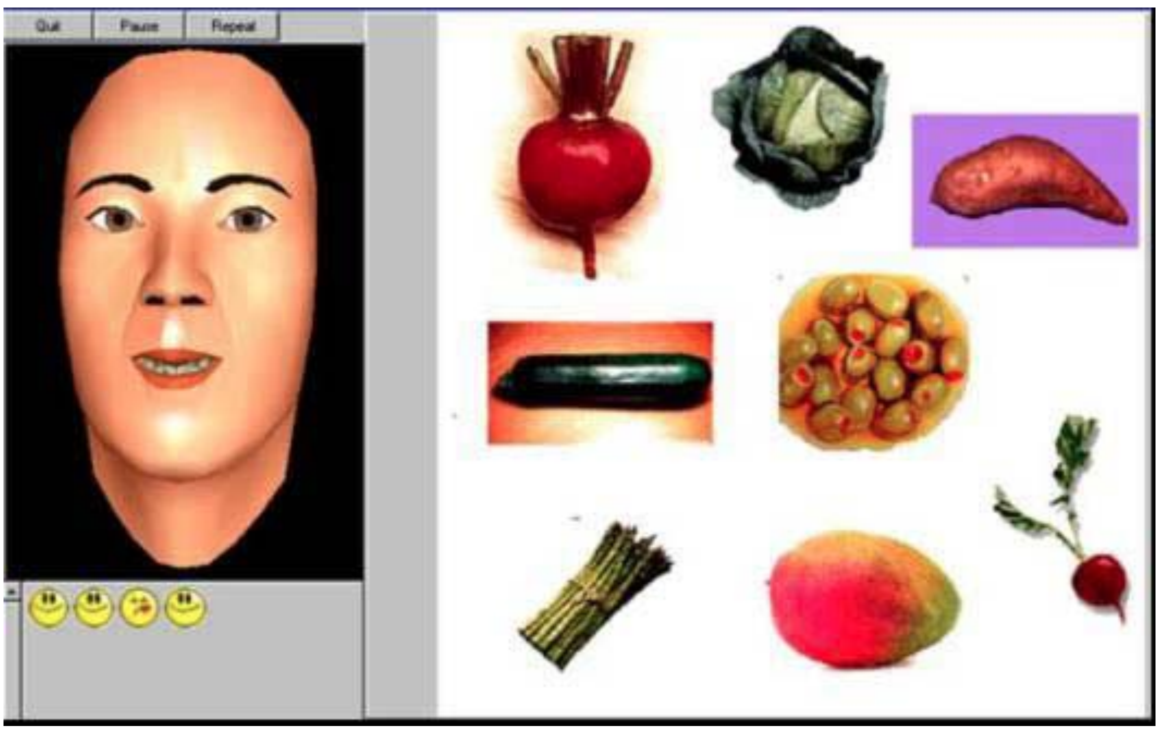

Figure 32. Baldi™ 's interface consists of the talking head with pictures representing words that the child must learn.

Baldi**™** was incorporated into a vocabulary learning game, called Language Player, in which children had to recognize and associate new spoken words to pictures representing them, spell new words and repeat new words after Baldi™ (Massaro and Light, 2004; Bosseler and Massaro, 2003). Correct choices were awarded a happy face, and incorrect choices an unhappy face in a scoreboard section of the interface. Figure 32 shows Baldi™'s interface.

Bosseler and Massaro (2003) used Baldi™ to help children with autism acquire new vocabulary. In two studies, Bosseler and Massaro used the Language Player program to teach children with autism new vocabulary and grammar. In the first study, 8 children with autism between the ages of 7 to 12 years old used the program twice a week for six months. The results showed a significant increase in vocabulary acquisition and an assessment 30 days after the last time the program was used, showed a new vocabulary retention rate of 91%. Seven of the eight children seemed to enjoy using the program and viewed Baldi™ as a social partner, talking to him and showing him to others who were present. The children also responded to the scoring scheme of happy and unhappy faces. In the second study, 6 of the children who had participated in study 1 used the program to learn additional vocabulary in a procedure similar to the first study. The purpose of this study was to assess whether the children could generalize learned vocabulary to new image stimuli and whether the learned knowledge could be transferred to a new environment and transfer to natural speech outside of the clinic. In addition to virtual rewards presented by the program (smiley face stickers), food rewards and/or verbal praise from the researcher were necessary to keep 5 of the children motivated throughout the study. The results from the study showed that the learned vocabulary could generalize to new images and that it could transfer outside of the computer environment.

In another study, Massaro and Light (2004) investigated the efficacy of the system for teaching new vocabulary and improving articulation for children with hearing disorders. 7 children with hearing disorders (using a variety of assistive hearing devices) received a total of 6 hours of individual training over 21 weeks. Each week two 15-minute sessions in which the system was used were administered. During the sessions, the children were instructed to repeat words and sound segments after Baldi™. The spoken speech's speed was reduced by 30%. Each participant used the CBSLT system in the presence of one of the researchers.

At the conclusion of the study, the participants' speech perception and production were evaluated. Initially, the researchers used an ASR module to record participant's speech and prompt them to repeat words and sounds after Baldi™. However, the ASR module proved to be too imprecise and provided confusing feedback to the children. In response, the researchers decided to use a Wizard-of-Oz approach to record speech samples of children. Two groups of human judges evaluated the children's speech samples to measure speech production improvements. To evaluate speech perception, a test module within the Language Player was used. At the conclusion of the study, both speech production and perception were improved for all of the children. Furthermore, the children were able to generalize learned sounds to new words not included in the sessions. In a follow-up post-test 6 weeks after the end of the study, speech production had somewhat deteriorated, showing that the improvement was likely due to the use of Baldi™, rather than other factors.

ARTUR

Bälter et al. (2005) developed a prototype of a computer system for speech intervention for children with hearing disorders for use in the absence of SLPs. The system aimed to identify problematic articulations and provide corrective feedback. An animated head, with exposed internal parts of the face and mouth, referred to as the *ARticulationTUtoR* (ARTUR), was constructed. ARTUR was utilized to provide corrective feedback. The researchers hypothesized that, for children with hearing problems, the visualization of the movement of vocal organs (including the hidden parts of human head involved in speech production) would be more useful than acoustic signal visualization. A database of possible errors and instructions on feedback responses was constructed. Each feedback response consisted of spoken commands and corresponding animation mapped to one or more potential speech errors. In the final implementation of the system, audio input was to be combined with video footage of the user for more accurate categorization of articulation error. Figure 33 shows ARTUR's interface.

To use the system, the user responds to a prompt asking for him or her to repeat a word. When the word is repeated, the system analyzes the input speech and identifies articulation errors if present. Corresponding feedback is then provided to the user. The researchers decided to conduct a preliminary Wizard-of-Oz study of the system, as it was not fully implemented yet. The study involved two groups of children. The children in the first group were six years old and the ones in the second group were between nine and eleven years old. In addition to children, an adult with English as second language also participated in the study. Qualitative data in the form of interviews with the participants and the wizard were conducted.

Figure 33. ARTUR's User interface providing articulatory feedback (Bälter et al., 2005)

The qualitative data from the study demonstrated that the children, especially the older group, liked the idea of playing with a computer and being given explicit feedback. However, while they (and especially the older group) liked the program in general, they found the visual feedback confusing and unhelpful. This was found of both the image representation of speech organs and the accompanying animation. The children suggested that more game-like features, such as rewards and high scores, could be added to the system to make it more engaging. Also, they found the system's user interface, as well as, the anatomy of the vocal tract (e.g. the hard palate) hard to understand and use. When compared to interacting with the SLP, older children described interacting with the CBSLT system as more relaxed.

The adult user suggested that it should be possible to make a few practice pronunciations before being evaluated. The wizard who simulated automatic feedback observed that the choices available for feedback were too general and imprecise. Many situations were not covered and, as a fallback strategy, encouragements were used after repeated errors. The wizard also suggested that repeating the same feedback after a repeated error is not a good strategy and does not provide additional help on how the user can work on correcting the speech error. Finally, he suggested that general ambiguous feedback should be used for times when errors are hard to classify.

Flappy Voice

Flappy Voice (Lan et al., 2004) is a mobile game to teach speech timing and prosody skills for children with *childhood apraxia of speech (*CAS). Flappy Voice is a variation of the open-source game Flappy Bird that replaces touch controls with input voice from the child. The goal of the game is to control the flight of a bird while avoiding hitting obstacles. In Flappy Voice, the child's vocal loudness is mapped to the bird's position by means of a smoothing filter. Thus, the children control the bird using the duration and amplitude of their voice. The level of difficulty of the game is configurable (via an interface operated by the supervising SLP). In a preliminary evaluation, 6 children, 3 with CAS and 3 controls, played with the game and found it fun and engaging. Clinical or therapeutic outcomes of the game were not evaluated. Figure 34 shows Flappy Voice's interface.

Figure 34. Flappy Voice interface. The bird's movements are controlled by the child's vocal loudness.

visiBabble and VocSyl

The *visiBabble* system, instantiated either as a tangible digital toy or as a software application running on a notebook computer is intended as an early speech intervention. It supports interventions targeting speech delays and interventions that encourage language and cognitive development for late-talkers (i.e., children who do not have a disorder but start speaking later in life) (Fell et al., 2006; Fell et al., 2004). The system processes infant vocalizations in real-time and produces brightly colored animated visualizations. The visualizations are intended to provide positive reinforcement of the production of syllabic utterances. In this system, the visualizations are used as stimuli to engage the children and elicit speech, rather than provide corrective feedback[38]. Figure 35 shows visiBabble's interface.

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[38] It can be argued that the stimuli provided by visiBabble and VocSyl should not be considered as "feedback" as their aim is not to provide corrective or even descriptive information (i.e., information intended to describe a state) to the user. Having taken this into account, in this discussion, I still refer to this stimuli as "feedback" as their main role is to respond to input from the user. Thus, in this section, I will use the terms "feedback" and "stimuli" interchangeably.

Figure 35. Two screenshots from the visiBabble interface (Fell et al., 2006)

In a similar vein, the *VocSyl* system also uses a software interface that provides engaging visualizations (sometimes combined with auditory stimulation) produced using input speech and vocalization analysis to motivate children to use their speech (Hailpern et al., 2009; Hailpern et al., 2010; Hailpern et al., 2012). VocSyl uses a suite of audio visualization modules to represent different audio features of speech (pitch, loudness, duration and syllables) in abstract visual representations, presented to children in real-time.

VocSyl was designed to motivate children on the autism spectrum disorder (ASD) to produce speech and speech-like vocalizations. One of the goals was to provide children with a persistent visual representation of their speech that would facilitate reflection and a new experience of language skills. An initial study with 5 children with ASD showed that the audio and visual stimulation increased the rate and duration of speech-like vocalizations (Hailpern et al., 2009). The study found that each of the children responded to at least one form of feedback and that the most effective feedback varied for different participants (i.e., only some participants responded to visual stimuli while others responded to auditory stimuli or a combination of visual and auditory stimuli). They also found that the visualizations should be customized to some extent for each person (Hailpern et al., 2009).

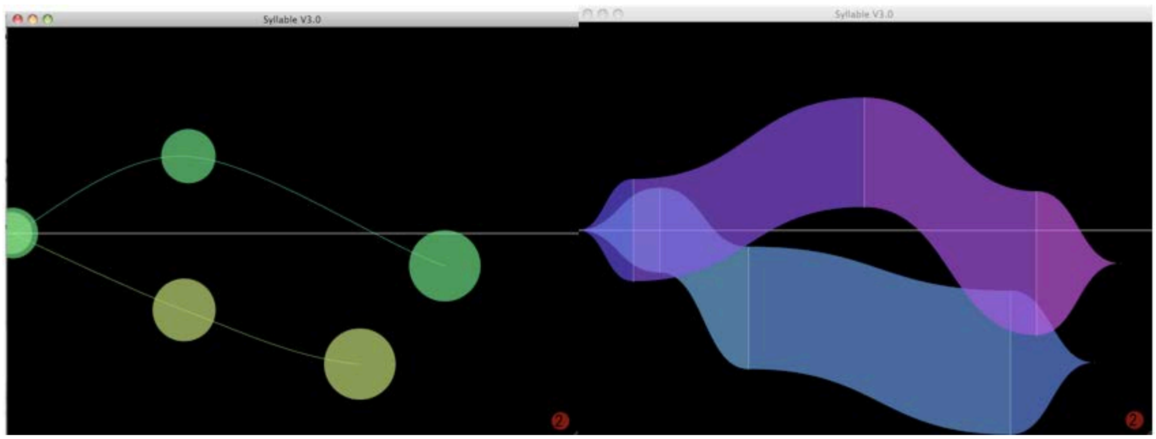

Figure 36. VocSyl visualizations to illustrate multisyllabic words (Hailpern et al., 2012)

A more recent application of the system supports the production of multi-syllabic speech production in children with autism, speech apraxia and speech delay (Hailpern et al., 2012; Hailpern et al., 2010). The goal is to use visualizations to illustrate differences in utterances and help with the ability to combine syllables both as word combinations and in single multisyllabic words. In the new version of the system, syllables are represented by discreet elements on the screen and emphasis, pitch change and pacing are represented by the diameter of the graphical element and position on the y-axis and x-axis, respectively. The researchers involved two children with ASD, two children with speech delays and four children without disabilities in the design of the system. Figure 36 shows VocSyl's interface.

Similar to visiBabble, VocSyl focused on engaging and motivating its users, rather than providing corrective feedback. Additionally, the system provided the visualizations as a communication aid to help SLPs demonstrate specific aspects (i.e., syllable location and volume) of the vocalizations to the children. It is apparent that if the corrective feedback was provided in the absence of SLPs or parents who facilitated their interpretation, the children would not have been as motivated to continue using their speech.

LinguaBytes and Explorascope

All the reviewed systems so far have been screen based[39], meaning that the main mode of communication with the user has been a software interface displayed on a computer or tablet screen. An alternative (and sometimes complementary) approach to screen-based interaction involves the use of *tangible and embedded interfaces* (TEIs).

Hengeveld et al. (2009) developed *LinguaBytes*, a set of digitally augmented dolls, pictogram cards, and puzzle pieces that were to be placed on

[39] With the exception of a version of visiBabble that is mentioned but not described in the literature (Fell et al., 2006).

an augmented play surface. The interface engaged children in interactive storytelling and puzzle-solving games. The interaction involved the narration of a story. The tangible items were created to correspond to keywords in the stories. The story was paused by the interface periodically after the mention of an object or character, prompting the children to place corresponding items on the augmented surface in order for the story to continue. Figure 37 shows LinguaBytes.

The items used in LinguaBytes were each embedded with *radio-frequency identification* (RFID) tags that were recognized by RFID tag-readers embedded in the play surface. With any given configuration of items, the system would narrate a corresponding multimedia story with sound and video. Parents and SLPs were provided with additional RFID tags, so that they could create new embedded objects (e.g., adding a RFID tag to the child's own plush toy).

The interface was designed for use in SLP-led language and communication skills learning for toddlers (between 1 and 4 years old) with multiple disabilities, such as cognitive and perceptual-motor disabilities. The goal was to devise a set of activities that would help children expand their vocabulary and to elicit a greater amount of communication between the child and others.

In evaluations of the TEI, Hengeveld et al. (2009) observed that the children showed longer attention spans and that the TEIs themselves slowed down the interaction, which provided the children with more control over the timing of activating the interactive material. The researchers concluded that the TEI afforded a more natural and accessible interaction for the children than screen-based storytelling and narration interfaces.

Figure 37. *LinguaBytes'* interface (Hengeveld et al., 2009)

Another tangible interface was developed for interactive storytelling targeting the same age group of children with multiple disabilities (Hummels et al., 2006). *Explorascope (E-scope)* consisted of a wooden toy in the shape of two rings, one non-moving ring on the bottom and a rotatable one on top. Both rings on the toy were wirelessly connected to a computer with a screen. The toy was designed to implement an interactive storytelling activity and could be used in one of two ways: one method involved the child or SLP to move it over tagged images on the floor. Motions would activate a story line corresponding to the chosen images. Another method required the child to rotate the upper ring of the toy until a desired image was visible through an opening in its cover. The story line corresponding to the image would then be activated. Figure 38 shows E-scope's interface.

Figure 38. *E-scope's* interface (Hummels et al., 2006)

A prototype of the system was used in a preliminary study with three children with multiple disabilities. Observations from the study were overall positive and showed that two of the three children were motivated to interact with the toy. In interviews conducted post-study, three SLPs who were present during the study found the approach promising because of its adaptability, playful approach and integration of multimedia material.

A web-based speech intervention system

Parnandi et al. (2013) are developing a web-based interface for remote administration and evaluation of speech exercises for children with childhood apraxia of speech (CAS). The goal of the system is to provide a web interface to allow a SLP to remotely assign speech production exercises to each child. The child would then practice these exercises at home using an app running on a mobile device. During interaction, the app records and streams the child's speech to a backend server. At the server, the speech samples are analyzed and scored automatically. An ASR module is proposed that analyzes input speech using a hidden Markov model (HMM) that compares the child's utterances with a database of expected mispronunciations. The therapist can then review the individual recordings and the automated scores through a web interface, provide feedback to the child, and adapt the training program as needed.

A prototype of the system was developed where digitized images from the Nuttfield Dyspraxia Program (NDP3) were used to elicit speech samples from children. In a pilot study, four children with CAS and four SLPs used the interface in one session in which children were prompted to repeat 10 words. The study was conducted in the presence of the SLPs and no automatic feedback was provided or evaluated. The results of the study were encouraging in that the children, SLPs and parents all liked the idea of using such a system to be able to conduct speech exercises remotely. However, they identified the need to create more engaging content and adding audio, graphics and means of engagement, such as scoreboards and badges. In the study, the focus on the user's end was in elicitation of speech, rather than providing automatic feedback. The use of ASR was mainly restricted to classifying input speech in the backend for ease of use by the SLP's. The possibility of using ASR to provide feedback to children was identified but not focused on. This approach of focusing on elicitation rather than correction has also proven to be effective in the use of CBSLTs that support rehabilitative interventions for adults with aphasia (Jokel et al., 2009).

Other systems

Several other CBSLT systems that are developed to support speech intervention for children with speech sound disorders are described in the literature. However, these research projects have either not presented any evaluations or have provided fragmentary description of the system's functioning, making it difficult to assess their strengths and weaknesses. I will briefly describe two of these systems here. Unfortunately, based on available information, I am not able to assess their usefulness.

Chaisanit et al. (2010) described a CBSLT system to help SLPs teach the articulation of vowels to children with hearing disorders. The system was developed for the Thai language and uses computer animation to display internal and external speech organ movements during the articulation of specific vowels. They evaluated the system with 10 hearing impaired students who were divided into a control and an experimental group. They found a significant difference in learning effects between the two groups. Additionally, both the children and their teacher enjoyed using the system. However, information about how much time the children spent with the system, how learning effects were defined and how the evaluation was performed was not presented.

Bastanfard et al. (2010) are developing a CBSLT system to assist with speech intervention for children with hearing disorders. The system is envisioned for use in the clinical context, in the presence of a SLP, as well as, in the home setting. Video samples of an SLP articulating specific sounds, as well as, drawings of internal speech organs are used as feedback. No user evaluation was reported.

Review of CBSLTs Targeting Children with Language Disorders

Similar to applications developed for practicing speech, recent years have also seen a surge of systems that aim to support intervention for children with developmental disorders that affect social skills and the function of language (i.e., language pragmatics). These applications are developed for children with the autism spectrum disorder (ASD) and similar disorders (i.e., Asperger's Syndrome). Examples include Touch and Learn: Emotions[40], Model Me Going Places 2[41], Autism iHelp[42], SeeTouchLearn[43], Autism Emotion[44]. In fact, apps that

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[40] https://itunes.apple.com/ca/app/touch-and-learn-emotions/id451685022

[41] https://itunes.apple.com/ca/app/model-me-going-places-2

[42] https://play.google.com/store/apps/details?id=com.mindpacetech.Autism_iHelp_Play

are useful for children with ASD and their parents are increasing at such a high rate that an app, Autism Apps[45], is developed to present its users with a comprehensive list of other apps for children and their community. In addition to applications specifically developed to support language intervention and social skill practice, many other applications that encourage the use of language, for example through story telling, narrative building and expressive vocabulary expansion, are used by SLPs and parents to support language skill development, as reported informally in blog and news posts (e.g., by Mautone (2013) and Rosa (2013)). Some examples include Pictello[46], Book Creator[47] and Kid in Story[48]. While studies to evaluate their usability and efficacy are yet to be conducted, the potential benefits of these applications for language training and intervention are clear. Here, I will limit my review to CBLSTs that focus on language intervention,

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[43] https://itunes.apple.com/ca/app/see.touch.learn./id406826506

[44] https://itunes.apple.com/ca/app/autism-emotion/id550027186

[45] http://touchautism.com/app/autism-apps/

[46] https://itunes.apple.com/app/pictello/id397858008

[47] https://itunes.apple.com/us/app/book-creator-for-ipad/id442378070

[48] https://itunes.apple.com/us/app/kid-in-story/id594403164

specifically targeting disorders that affect language pragmatics and have at least one peer-reviewed published description or evaluation.

pOwerball

Brederode et al. (2005) have developed *pOweball,* a multiplayer tabletop game for both children with multiple disabilities (including physical and learning disabilities) and children without disabilities to play together. To play pOwerball 2 to 4 players sit around a table onto which graphics are projected. The goal of gameplay is to free creatures blocked in structures by controlling virtual balls. The players can control the path of the balls by using single switches assigned to them. The game is designed such that each player can combine collaboration and competition in his or her gameplay. The aim of the game is to facilitate more social contact for children with disabilities (with each other or with children without disabilities) and to improve social skills. The game was developed using a participatory design approach that incorporated extensive feedback from children with disabilities (see section Appendix B for more information about its design process). Figure 39 shows children playing with pOwerball during an evaluation.

Figure 39. Children playing with pOwerball during evaluation (Brederode et al., 2005)

In an evaluation with 18 children with multiple disabilities between the ages of 8 and 14 who played the game in 6 teams of 3 players each (each team playing for a 40 minute session), the researchers found that the game was accessible and all children could understand the game mechanics and utilize the technology. More importantly, the game encouraged social interaction and collaboration.

SIDES

Piper et al. (2006) developed a multiplayer tabletop game for social group therapy for children with Asperger's Syndrome, called *Shared Interfaces to Develop Effective Social Skills* (SIDES). 12 students (12-14 years old) with Asperger's Syndrome and other conditions leading to various social skill challenges, along with their mental health therapist were involved in the design and evaluation of the game. The game is designed for use in the school setting with peers as interaction partners and in the presence of special education teacher. The researchers employed a participatory design approach that I will review in Appendix B.

SIDES resembles a cooperative board game (with minimized competition) whereby each player has a set of arrow pieces that can be placed on the board to form a path for a frog to follow to reach a destination. Scores are awarded when the path intersects with other insect pieces. The players are to cooperate to build an optimal path together. The cooperative game is implemented for the DiamondTouch tabletop system that can detect specific user's touch and input.

Initial evaluation with 5 students showed that while the game was engaging and enjoyable, it was hard to enforce turn taking and sharing rules. In a subsequent iteration, computer-enforced game rules including turn-taking order and virtual piece ownership were implemented. In a second series of evaluations with 8 student participants grouped into 2 teams of 4 players, the researchers found that the children enjoyed the imposed order. The adult mental therapist found that the computer-enforced order freed him up to focus on skill development using the game. The researchers found that using a tabletop system that could identify each player uniquely was very useful for implementing a face-to-face collaborative game that the players perceived to be fair and enjoyable. However, the constraints of the technology, which required children to remain seated and not bump the table, were also noted. They found that the computer could play an important role as a fair and consistent referee in the game. The children's social skills therapist observed that focusing on gameplay and engagement was key in the system's success, as it implicitly encapsulated the social skill learning tasks in the gameplay and supported social turn taking and collaboration through gameplay. Figure 40 shows students using SIDES to play together.

Figure 40. Students use SIDES to play together (Piper et al., 2006)

ECHOES

Frauenberger et al. (2011; 2012b) and Bernardini et al. (2013) have developed ECHOES, a serious game for children with autism to practice social communication skills with an automatous virtual agent. The system is designed using a participatory design process (described in Appendix B) and incorporates input from children with high-functioning autism and their teachers and parents into the system. The game involves the child exploring a virtual garden with help from a virtual agent who acts as peer and tutor. The system is implemented for a large display that is augmented with gaze and touch tracking. Virtual objects in the garden transform when the child touches them, providing a sense of magic. It is designed for use in the school or home setting. Figure 41 shows a child interacting with SIDES.

The researchers chose to employ an autonomous agent in the system design because previous research suggests that using an autonomous agent might promote generalization and retention of information (Grynszpan et al., 2008; Bosseler and Massaro, 2003). Additionally, the researchers plan for the system to be used in the absence of adults and, thus, having an autonomous agent to keep the children company would be desirable (Bernardini et al., 2013).

Figure 41. Child user interacting with ECHOES (Bernardini et al., 2013)

19 children with autism (average age 8 years) participated in a study where they interacted with ECHOES for periods of 10-20 minutes several times a week for 6 weeks. The researchers found that many of the children's bids for the agent to interact with them increased over time and that the children exhibited interactions (such as greetings) towards the agent that they did not normally exhibited in human-to-human interactions. The system's focus on engagement was found to be effective at keeping the children interested during the interaction. The researchers concluded that this approach has potential to engage children in new ways and encourage them to practice social communications skills in a safe setting before transferring the skills to the real world.

Other Relevant Systems

Some CBSLTs have been developed to help children with autism with facial expression recognition and production. Cockburn et al. (2008) found that the use of games, even for short amounts of time, can help children with autism develop facial expression and face recognition skills. Tanaka et al. (2010) implemented a game, *Let's Face It!,* which motivated children with autism to practice facial expressions, such as smiling and frowning. The system used computerized facial recognition to recognize its users facial expression during gameplay. The children were motivated to practice making facial expressions, since these were needed in order to progress in the game.

Other CBSLTs have targeted learning disorders. *The Arrowsmith Program* is designed to support intervention targeting learning disorders disabilities through exercises and games (Arrowsmith Program, 2007). The approach is based on the conjecture that problems in high level functions, such as writing and copying, have their underlying root in disorders of specific elemental cognitive abilities, such as symbol recognition and sequencing (Young & Burrill, 1997), and that games and exercises that target and strengthen these underlying skills will also improve high level functions and learning more generally. The first step of the program involves a detailed evaluation and assessment process that identifies elemental cognitive disorders for each student. An individualized task-oriented program follows that challenges and alleviates the identified deficit through playing customized games.

A number of reports examined the program's effect in select schools in the Toronto District School Board (TDSB) where it was introduced. They have documented its positive impact on the students' learning abilities and have also observed that students using the program needed fewer additional resources

(Arrowsmith Program, 1998; Arrowsmith Program, 2007). Despite these promising results, the main conjecture of the approach has not been supported with empirical data yet.

Summary

In this appendix, I reviewed a series of CBSLT systems designed to support speech and language interventions for children. In chapter 3 of the dissertation, I have presented a synthesis of results of this review to inform the project. Tables 9 and 10 in Appendix A summarize the results of this review.

Appendix B. A Review of Participatory Design with Children

Participatory Design (PD) (Greenbaum and Kyang, 1991; Schuler and Namioka, 1993) is a design methodology that emphasizes the incorporation of user domain knowledge and recognizes the importance of collaborating and co-creating technology with users and their community. An essential technique of PD is to actively engage users of technology in its design. Originally, PD was used to develop technologies for the workplace; however, it became apparent that it also offers great value to many other areas of design and development including designing for users with disabilities (Kensing and Blomberg, 1998) and specifically designing with children with disabilities (Hourcade et al., 2014; Frauenberger et al., 2012a).

As described in chapter 5, I used a variation of PD, *PD with Proxies*, in the *Rafigh* project. In this appendix, I will present previous research describing the rationale and application of participatory design with children with and without disabilities and adults with disabilities.

Participatory Design with Children

In recent years, several PD methodologies have been developed specifically for including children in the design process. *Cooperative Inquiry* is specifically developed to allow children to be design partners and collaborate with adults to come up with novel design ideas (Druin, 1999). The method views children as potential designers and aims to facilitate their abilities to be design partners through accessible and intuitive methods. Cooperative Inquiry uses a series of techniques such as *Bag of Stuff* and *Stickies* to prototype and critique ideas. *Bag of Stuff* uses low-tech tools such as paper, pens and craft material to allow children to come up and express novel design ideas. *Stickies* uses small pieces of paper with adhesive glue on the back to help children express reasons for liking or disliking a design or to suggest new ideas. This method is typically used with small groups of children over a long period of time. Guha et al. (2008) are developing an inclusive version of Cooperative Inquiry that provides provisions for involving children with disabilities.

Two other related approaches, Bonded Design and Informant Design, also include children as co-designers. *Bonded Design* views children as design partners but also questions whether the hierarchies between adults and children can be overcome during the design process (Large et al., 2006). *Informant Design* incorporates children's input into design but does not view the children as co-designers (Scaife et al., 1997). In this method, children are given an informant role, where they provide feedback and input at different stages of the design process. The main difference between this method and Cooperative Inquiry is that the researcher does not solicit input from the children at every stage of the project and only at select times.

Participatory Design and Assistive Technology

Oftentimes, designers of assistive technology do not have direct experience of the physical and/or mental conditions that necessitate their designs. This may be the case even for researchers who have disabilities themselves and are themselves users of assistive technology. Each person's use scenario may be unique and it is important to develop and utilize methods that allow for the incorporation of different perspectives and experiences into the design process.

It is essential for technology designers to work closely with representatives from the population for which they are designing for, so that they can have a better understanding of the potential impact of the systems they design on real users and their community. Additionally, the importance of accommodating designers and co-designers who themselves have disabilities and thus, "insider knowledge", in the design of assistive technology is becoming increasingly apparent.

Many previous projects have used PD to develop assistive technologies with users with disabilities. Most of these studies are conducted with adults with disabilities, rather than children with disabilities and, yet, the methodological implications are relevant here. Recently, more participatory design projects are being conducted with children and specifically children with disabilities. The topic of designing for and with children with disabilities has been discussed in several international workshops in recent years (e.g., see Hourcade et al., 2014). Frauenberger et al. (2012a) have argued strongly for engaging children with disabilities and their community in the design and evaluation of computational interfaces, arguing that the three identified benefits of using Participatory Design, namely 1) better understanding of requirements, 2) building realistic expectations in target groups and 3) empowerment of marginalized groups, are amplified in this context.

Including individuals with significant communication and language disabilities in PD is challenging because of their limited language ability to describe their needs and opinions. This is compounded in the case of children because of it is more difficult for them than for adults to participate in abstract or hypothetical discussions and scenarios. For these reasons, some researchers have employed caregivers as "proxy users" to explore the needs of individuals with disabilities (Boyd-Graber et al., 2006). In the case of children, proxy users can include the children's parents, teachers and other children who do not necessarily have the same disability that impairs language. While this method can provide insights into the needs of individuals with disabilities, it is important to involve proxy users in addition to children with disabilities and verify ideas or results gained from working with proxy users in real-world situations.

Participatory Design with Children with Disabilities

Several recent projects have explored using PD with children with disabilities to design various systems, including serious games and intervention systems, among others. Hirano et al. (2010) used a participatory design with proxies method to design and evaluate, *vSked*, a visual scheduling tool to support classroom activities for children with autism. To inform their design, they identified and involved adult stakeholders, 10 teachers and 3 SLPs, and conducted interviews with them and observed their classrooms and sessions over nine months. They incorporated the results into a working prototype that they co-examined with their community design partners in two sessions. Using feedback from these sessions, they built a working prototype that was evaluated in the classroom context. Both staff and students liked using the prototype and wanted to continue using it.

The researchers found that incorporating adult stakeholders in the design process was very helpful in building a relevant product. They decided not to involve children with autism directly because the researchers thought that "the burden of involvement" would be too high for the children. Similarly, Kientz et al. (2007) used the help of adult proxies (caregivers, parents and teachers of children with autism) to inform the design of a wearable interface to detect self-stimulatory behavior in children with autism. They described the social and behavioral difficulties of working directly with children with disabilities as design partners.

Brederode et al. (2005) involved children with different physical and learning disabilities as informants in the development and evaluation of *pOwerball,* an augmented reality tabletop tangible game to encourage collaboration and social interaction for children with mixed abilities. The researchers spent time observing children with disabilities in the classroom and at play with computer games and board games. They interviewed 31 children with physical disabilities about their favorite games and the elements that they like about them. Additionally, 20 observation sessions where children were playing computer games, board games and arts and crafts activities, were conducted. Several design goals from these sessions were incorporated into a game concept that was evaluated with 6 children with and without learning difficulties. The children provided useful feedback that was incorporated into the game concept.

Next, a working prototype of the game was developed and evaluated 18 children with various physical and learning disabilities. The children were split into 6 groups of 3 children each. Each group played the game for 40 minutes and the sessions were videotaped and analyzed later. The children were also interviewed about their experience following gameplay. The researcher argued that involving children as design informants provided useful insider information about their likes and dislikes around the game and created empathy and understanding between the researchers and the children without putting too much stress or pressure on the children.

Other projects have aimed to include children with disabilities themselves directly in the design process. In the ECHOES project, Frauenberger et al. (2011; 2012b) worked with two children with high-functioning Autism and one child with an undiagnosed language disorder, as well as, 30 typically developing 6-years-old children, on the design of a technologically-enhanced learning environment to scaffold the social skill development of both typically developing children and children on the high functioning end of the Autism Spectrum Disorder (ASD) or Asperger's Syndrome (AS).

After establishing a trusting relationship with the children and their parents through regular visits and classroom observations at the school and attending parents' support group meetings, the researchers conducted a series of design sessions with the children. The first three series of sessions were conducted with low-tech physical objects that were used to inspire reflection and imagination around a given scenario. In the first activity, the children were presented with a *treasure box* containing various ambiguous objects that they had to figure out how to interact with. In the second activity, children were presented with sets of three objects and asked to identify one as different and explain why. These first two activities provided researchers with insights around the kind of objects and affordances that are of interest to the children. In a third scenario, the children were presented with incomplete comic book scenarios and narratives that they had to complete. A specific object was to be used in each narrative.

After these activities, a series of digital prototypes were designed and shown to the children who provided feedback about them. The researchers found that working with children was rewarding and provided information that otherwise would have been difficult to come up with. Additionally, they found that finding a balance between the benefits of participation and risks of causing stress or pressure was important. Finally, they found it essential to *interpret* and *translate* children's feedback and ideas into realistic and practical design choices using a designerly approach in such a way that the interpretations stay true to the core messages of the children's ideas (Frauenberger et al., 2012b). In this project, the researchers followed a *Research through Design* methodology (Zimmerman et al., 2007).

The ECHOES project was inspired by *the Reactive Colours* Project in which children with autism were involved as key informants in the design of an interactive software system, *ReacTikles* that involves its users in engaging and relaxing activities (Keay-Bright, 2007). To inform the design the researchers worked closely with a special education school. Initially, they visited school classes and conducted an audit of existing educational technology at the school. This was followed by discussions using ideas for the system expressed in sketchbooks with school staff. Next, they showed a series of low-fi storyboards that demonstrated the basic functionality of the system. After getting feedback from the adult participants, they developed an initial version of the system. They conducted an evaluation of the system with children with autism. The children's interaction with the system was videotaped an analyzed later and they were asked for feedback after the interaction using questionnaires. Ideas from these observations were incorporated into a new version of the system adapted for the Smart™ Interactive Whiteboard. The system was evaluated with 6 children with developmental disabilities.

The results showed that the system was able to keep the children focused on tasks but was not successful at promoting sharing and turn taking. The project demonstrated that it is possible and important to include children with autism in the design of digital systems directly. Additionally, it showed the importance of creating a relationship with schools and especially the teachers of children with disabilities who provided valuable feedback about the system (Keay-Bright, 2007).

Piper et al. (2006) involved children with a range of disabilities including Asperger's Syndrome and autism, in the development of SIDES, a cooperative tabletop computer game for social skills development. 12 students (12-14 year's old) with Asperger's Syndrome and other conditions leading to various social skills challenges, along with their mental health therapist participated in the design and evaluation of the game. The researchers used a combination of observation and individual and group interviews to inform iterations of their system. In addition to attending the school social skills classes, the researchers conducted a series of interviews with the school mental health therapists and a SLP. This initial fieldwork provided them with an understanding of the current approaches in social skill education and therapy. They found that interviewing children one-on-one put too much pressure on the child and instead decided to conduct interviews in groups. Input from the field studies and interviews resulted in a paper prototype of a collaborative game that two teams of students played. After initial gameplay, the researchers conducted group interviews and brainstorming with the participants.

The game was then implemented for the DiamondTouch tabletop system. Initial evaluation with students showed that while the game was engaging and enjoyable, it was hard to enforce turn taking and sharing rules. Interviews with the students confirmed this, with some enjoying the game while others feeling left out. In the next version of the game, computer-enforced game rules were implemented. Further evaluations showed that different groups of students enjoyed the imposed order and, specifically, the adult mental therapist found that the computer-enforced order freed him up to focus on skill development using the game. Despite having mental disabilities, the students in this study were able to contribute significantly to the development of the game (Piper et al., 2006).

Millen et al. (2011) are developing a method to include children with autism in the design of new collaborative virtual spaces in the form of games that support social competence. Their proposed method involves the use of templates and personas to aid with structuring brainstorming activities that might otherwise be daunting for the children. They tested their method with 3 children with autism and observed that while the activities were overall successful in generating new ideas, the abstract concept of personas was confusing.

Benton et al. (2011) introduced a methodology for PD with children with autism disorder spectrum, IDEAS, specifically for the development of new software interfaces. The method relies on customizable sessions that rely heavily on the use of templates and computer mock-ups to help children participate in design. An initial user study with 10 children with autism disorder spectrum was promising and showed that most of the children were able to use the method to generate ideas for a new mathematical game.

In a study aiming to develop a communication application for individuals with cognitive disabilities, Dawe used a "technology probe" (an early prototype) (2007). The probe was developed on the basis of qualitative data (interviews with 20 families of children with cognitive disabilities). It was used to elicit suggestions and ideas from two individuals with cognitive disabilities and their families. Dawe argued that using a technology probe could be an effective tool to include individuals with significant cognitive disabilities in the design process because it facilitates dialogue and the necessary communication processes. The use of a probe allowed the participants to express ideas through actions in relation to the technology. The concrete instantiation helped overcome difficulties that the potential user may have in expressing their ideas verbally and in engaging in what otherwise could be abstract or hypothetical discussions (Dawe, 2007). Dawe (2007) further argued that having a concrete object (even in early versions) that can change and be modified in response to users' suggestion and requests has the potential for creating a sense of ownership and empowerment in the user, as his or her input can visibly impact the technology being designed.

Anthony et al. (2012) conducted a one-day PD workshop with 12 postsecondary students with various learning disabilities. In the workshop, students interacted with two prototypes in teams, and they provided feedback and design ideas to the researchers. Post-workshop evaluation surveys showed that the students found the workshop engaging and relevant. They felt empowered by being included in the design process and motivated to engage in discussions and hands-on activity. The researchers identified several factors that contributed to the success of the approach, including consideration of communicative differences and a focus on relating the projects to the participants' personal lives.

The above examples, regardless of the diverse populations that have participated in PD for the development of assistive technology, help identify two main characteristics of these participatory methods: first, by including users in the design process, these methods allow for the uncovering of valuable domain expertise (Visser et al., 2005). Second, a challenge when using these methods is to come up with appropriate communication tools (e.g., alternatives to spoken or written language, lo-fi and/or high-fi prototypes, etc.) that allow for the expression and integration of this expertise (Sanders and Stappers, 2008).

Participatory Design with Adults with Disabilities

In addition to the above projects, an examination of a number of projects that have used PD with adults with disabilities can provide insights onto how this approach can be applied in different scenarios. Wu et al. (2004) used PD with a group of 6 individuals with memory loss (amnesia) to develop a computational tool to help with the problem of disorientation. The researchers found that working with this target population as design partners allowed them to gain a better understanding of their living conditions and to gain access to their personal expertise through “mutual learning”. The researchers used paper tools, such as meeting agendas and drawn use-case scenarios. The research resulted in the development of a memory aid software application for use on a *Personal Digital Assistant* (PDA).

In another study, Moffatt et al. (2004) used PD to develop an *Enhanced with Sound and Images* (ESI) planner for the PDA for with people with aphasia. Users provided feedback on different stages of prototyping, from brainstorming to low-fidelity paper prototyping to high-fidelity software prototyping (Moffatt et al., 2004). The project had started with brainstorming and prototyping with one person with amnesia (unfortunately, this participant passed away). Subsequent to this, three other people with similar conditions collaborated with the researchers in later stages of development. In an evaluation, the ESI planner was compared to a *Not Enhanced with Sound and Images* (NESI) planner, with 8 users with aphasia participating as evaluators. Although the researchers observed that the performance of the participants was very diverse, the results provided useful knowledge about design tradeoffs (e.g., the NESI planner could be operated more quickly, but the ESI planner could be used more accurately).

In another study with eighteen older adult participants, Davidson and Jensen (2013) involved potential users in the design of a smartphone app to monitor health. Participants were divided into five groups, each of which worked on one of five possible applications. Analysis of the designs showed that the participants identified several novel health metrics (i.e., metrics that were not already included in existing apps). Also, the breadth of design suggestions indicated that the participants had a more holistic view of health that resulted in unique insights into design; this holistic view was not completely in convergence with that of the technology designers.

The use of low-tech and high-tech prototypes as tools for communication has been examined in different contexts. Gaillers et al. (2012) engaged potential users with aphasia, and conducted a series of workshops in which five participants used gestures (rather than spoken or written language) to express ideas and feedback about software and paper game prototypes. The researchers found that this method empowered the participants and also challenged the notion of researcher as "fixer". They argued that facilitating communication (through the development and use of accessible expressive tools and language) is a key element of using PD effectively with users with disabilities.

Finally, Wilson et al. (2015) went a step further by arguing for the development and use of "tangible design languages": non-verbal design representations that participants can use to communicate ideas and feedback to researchers during the design process. They demonstrated their method by successfully engaging adults with aphasia in the design of two therapeutic systems, *GeST* and *EVA Park*. They identified images, photo diaries and scenarios, tangible avatars and high-fidelity prototypes as elements that can help create a common language between researchers and users with communication disorders (Wilson et al., 2015).

Summary

In this appendix, I reviewed projects that have used different variations of Participatory Design with children with and without disabilities and with adults with disabilities. Previous research has underlined the potential of this approach for designing digital systems for children and provides a wide variety of strategies to approach design projects. In chapter 5, I applied a Participatory Design with Proxies approach to the design and evaluation of *Rafigh* prototypes.

Appendix C. Rafigh as Art Installation

I used *Rafigh* as part of an art installation on two occasions. In this appendix, I will describe my observations when using *Rafigh* in this context. I employed a *creation-from-research* approach as described by Chapman and Sawchuk (2012). I used *Rafigh* prototypes as art installations in order to understand better the living media technology it uses by actually deploying it in a different creative context. This approach falls within the *research-creation* domain defined by the Canadian Social Sciences and Humanities Research Council as "an approach to research that combines creative and academic research practices, and supports the development of knowledge and innovation through artistic expression, scholarly investigation, and experimentation" (SSHRC, 2014).

Prototype 2 as an Edible Installation

I first employed prototype 2 (described in chapter 5.4) as part of an art installation. I was inspired by the social aspect of the interacting with *Rafigh* and decided to use it in a new context, as a collaborative edible sculpture installation, in which collaborative activity in a group over time contributed to the growth of the mushrooms.

Since the installation was to be a in a large space, I decided to switch the speech activity to a reading activity. To this end, I adapted a Persian children's story, The Little Black Fish by Samad Behrangi and with illustrations by Farshid Meghali, into a digital interactive book on the iPad. Figure 33 shows screenshots from the storybook. The story was about a fish that was travelling from a pond to the ocean. While the theme of water was present and the idea of the audience helping the fish getting to the ocean by reading the story had some similarity to the concept of the mushroom being watered, a direct link between the two did not exist.

Figure 33. Screenshots of the story reading activity on the iPad

As an installation, *Rafigh* was displayed publicly to an audience who could interact with it by reading the story on an iPad. Upon the completion of each story, a user would get a message indicating that they had contributed to a score reflecting how many users had finished reading the story that determined how much water the mushrooms would receive. The volume of the water administered to the mushroom depended directly on how many people completed the story. The mushrooms would grow during the course of the installation and visitors could check back on the growth. Through this mechanism, different users could collaborate with each other and contribute to the growth and wellbeing of the mushrooms.

The installation was displayed at the International Conference on *Tangible, Embedded and Embodied Interaction* (TEI'13) in Munich, Germany (Figure 34). More than 60 people interacted with *Rafigh* with more than half of them finishing the story and, thus, contributing to the mushrooms' growth.

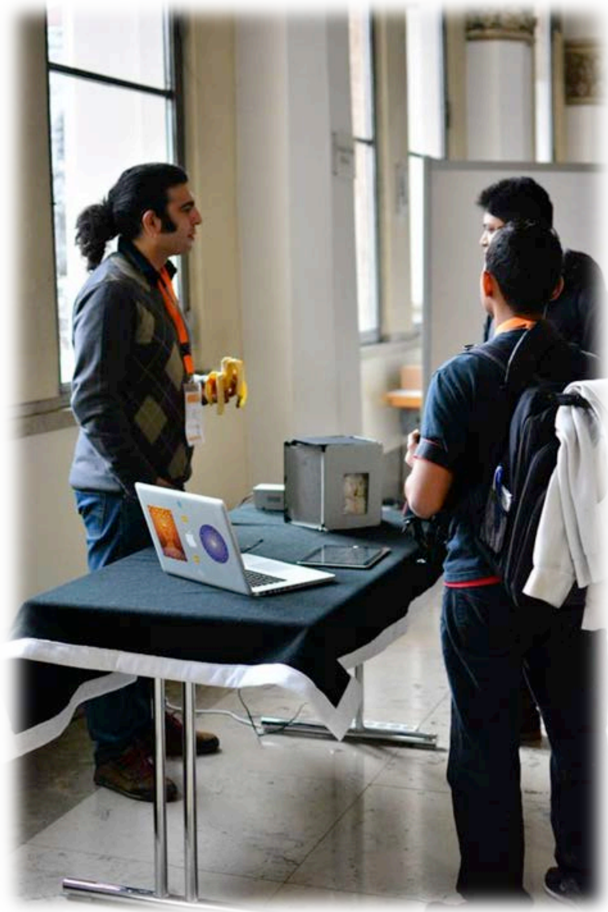

Figure 34. *Rafigh* as installation at TEI'13

The reception at the conference was mixed: while the participants were impressed with the concept of having living media as part of a digital system and were interested in collaborating with others to take care of the mushrooms, the slow rate of the mushrooms' growth (that was further slowed down because they were exposed to varying temperatures during transportation) was a challenge in keeping the participants interested. Additionally, the connection between the digital activity and the mushrooms' growth was not clear to many participants. Finally, after much use, the prototype was starting to fail structurally, making it apparent that for future iterations more robust prototypes were needed. These insights were incorporated into the design of prototype 3 (as described in detail in section 5.4). Figure 35 shows prototype 3 at different stages of growth.

Figure 35. Prototype 3: inside (left), after 8 days of growth (middle), after 12 days growth (right)

Prototype 3 as an Edible Installation

I also used prototype 3 (described in chapter 5.5) as part of an art installation. The installation was displayed at the *International Conference on Human Factors in*

Computing Systems (CHI'14) in Toronto, Canada (Figure 36). As the collaborative task, I used the same reading task as the one used at the TEI installation.

While the size of the conference was much bigger than TEI and more than a 100 people stopped at the installation, only a handful of participants actually finished reading the story. The fast pace of this conference and the large number of other demos and installations contributed to this aspect of the interaction and stressed the fact that interacting with *Rafigh* requires patience and extended amounts of time.

An important difference between the installations at CHI versus TEI was that the new redesigned prototypes were much more robust and also were often perceived as completed products. Several members of the audience asked whether they could purchase *Rafigh* and thought it was available commercially. I believe this shows that using rapid prototyping methods was effective at creating a more refined version of the prototype, a feature that was appropriate at this late stage of development.

Figure 36. Prototype 3 at the CHI'14 Conference

Summary: Rafigh as Collaborative Edible Art Installation

The two art installations described in this appendix allowed me to deploy *Rafigh* as a collaborative interactive artwork. By viewing the project in this light, I was able to understand the potential of the living media system in a manner different from the way described in the rest of this dissertation, a process that allowed me to identify a different audience for the system.

Appendix D. User Study Interview Questions and Answers

In chapter 6, I described two case studies that I conducted with *Rafigh*. I used a series of open-ended pre- and post-study interviews to gather information and data about the participants and their interaction with *Rafigh*. In the first part of this appendix, I will present the questions I used in the interviews. In the second part of the appendix, I will present Table 9 and Table 10 that summarize the qualitative data gathered during the interviews conducted in case study 1 and 2, respectively. I analyzed this data in section 6.5 to answer research questions posed in section 6.2.1.

Interview Questions (for the adult participants)

Pre-study Questions

1. Do you use computers, tablets or smartphones on a regular basis at home? If yes, please describe the device(s) and applications used.
2. Do the child participants use computers, tablets or smartphones on a regular basis at home? If yes, please describe the device(s) and applications used.

3. Do you have rules for when and how the child participant(s) should use digital device(s) at home? If yes, please describe them and describe why you have them.
4. Do you believe there are digital applications that would be beneficial for the child participants to use? Please explain why or why not.
5. Do you believe there are ways that the child participants can use digital applications that would be beneficial to them? Please explain.
6. Have any of the child participants been diagnosed with any disorders before? If yes, please describe the diagnosis and any interventions that they have participated in.
7. Do you want to encourage any existing or new behaviors in the child participants in the home?
8. Have you or the child participants participated in a study before? If yes, please explain.
9. Why are you interested in participating in the study and what would be a desired outcome?
10. Are there any other thoughts or ideas about the study that you would like to share?

Post-study Questions

1. Did you notice any changes in the child participants' behavior during Phase A? Please explain. Did you notice any changes in the child participants' behavior during Phase B? Please explain. Did you notice any difference in the child participants' behavior between Phase A and Phase B? Please explain.
2. During Phase B did the child participants made any statements about *Rafigh*? During Phase A or Phase B did the child participants made any statements about the digital applications they were using or not using?
3. During Phase B did you observe signs of interest or disinterest towards *Rafigh* in the child participants? During Phase A or Phase B did you observe signs of interest or disinterest towards the digital applications in the child participants? Please explain.
4. Can you describe how *Rafigh* works and how it is connected to the digital applications on the tablet(s)?
5. Did you have any conversations with the child participants about *Rafigh*? Did you observe any conversations between the child participants or between them and other people (visitors, family members, friends) about *Rafigh*? Please explain.

6. Did you observe any signs of responsibility or caring towards the mushrooms in the child participants? Please explain.
7. Did you notice any sign of increased interest in the child participants towards technology, nature or other themes related to *Rafigh*?
8. Do you think using *Rafigh* was beneficial for the child participants? Do you think it was beneficial for you? Please explain.
9. Do you have any suggestions on how to improve *Rafigh's* design? Do you have any suggestions on how the overall study can be improved?
10. Are there any other thoughts or ideas about the study that you would like to share?

Follow up Questions

1. Have you noticed any changes in the child participants' behavior since the study? If yes, please describe.
2. Have the child participants expressed or demonstrated interest in digital applications? Have the child participants expressed or demonstrated interest in nature, mushrooms or growing things?
3. Have you observed any increase in signs of responsibility, empathy or caring in the children? If yes, please explain.

4. Since the study have the children mentioned *Rafigh*, mushrooms, nature or any other subjects related to the study?
5. In retrospective, do you think *Rafigh* was successful in motivating the child participants to engage in target application use? Overall, do you believe participating in the study was beneficial to you and/or the child participants? Would you participate in similar studies in the future?
6. Are there any other thoughts or ideas about the study that you would like to share?

Interview Questions (for the child participants)

For the child participants, I used the following questions as guidelines and changed their wording appropriately such that the questions would be clear and easy children to understand and respond to.

Pre-study Questions

1. Do you use usually use computers, tablets or smartphones at home? If yes, please describe the device(s) and applications you use.
2. Do you have any favorite digital applications or games that you play? Can you describe them and why you like them?

3. Are there any digital applications or games that you don't like to use? If yes, why?
4. Are there any digital applications or games that you would like to use but have not used in the past? If yes, why would you like to use them?
5. Do you like nature? If yes, what do you like about it? If no, why not? Have you grown plants or flowers before? Please explain.
6. Have you had pets before? If yes, please describe your pets and how you care for them? Do you like to take care of pets and/or plants? If yes, what do you like about caring for them? If no, why not?

Post-study Questions

1. What did you like about *Rafigh*? What didn't you like about it? Would you like me to change anything in *Rafigh*? Would you like to use *Rafigh* again?
2. Did you like the digital applications you were using? Which digital applications did you like and which ones didn't you like? Why? Would you like to use them more in the future?
3. Can you describe how *Rafigh* works? Why did the mushrooms grow fast (or slow)?

4. Did you show *Rafigh* to anyone else? If yes, why and what did you say? What did they say?
5. Do you have any other comments, questions or suggestions about *Rafigh*, the digital applications, mushrooms, the study or any other related theme?

Qualitative Data Summaries

The following tables, Table 11 and Table 12, summarize qualitative data gathered in case studies 1 and 2 that were presented in chapter 6. The data was categorized based on the research questions that they were relevant to. The categories were i) statements on *Rafigh's* efficacy at motivating child participants to use target applications; ii) statements regarding *Rafigh's* ability to engage children by creating empathy and responsibility in them and the effect of using real mushrooms in the interface; iii) statements regarding the relationship between *Rafigh* and target application use; iv) statements on *Rafigh's* support for collaboration and communication in the home setting; and v) statements regarding the quality of the child participants' experience with respect to the slow responsivity of *Rafigh* and the ambient interaction it affords.

Relevant Research Question	Participant (s)	Statement/Observation/Action
RQ1	P1	P1 stated several times at different points during the study that "I have to use learning apps, so the mushrooms grow". He checked the mushrooms in the mornings and when coming back from school. He expressed interest in the mushrooms until the end of the study.
RQ2	P1	P1 referred to the mushrooms as "little ones" and "those guys". He stated several times during the study that "I have to use learning apps, so the mushrooms grow". He checked the mushrooms' growth regularly. During my visits, he had many questions about how the mushrooms grow, how they reproduce and what happens when they die.
RQ3	P1	P1 successfully described the relationship between *Rafigh* and his use of applications in the post-study interview. He stated several times at different points during the study that "I have to use learning apps, so the mushrooms grow".
RQ4	P1	
RQ5	P1	P1 checked the mushrooms in the mornings and when coming back from school. P1 requested to bring the harvested mushroom to the school to show to her friends.
RQ1	P2	P2 checked the mushrooms in the mornings and when coming back from school. At the beginning of Phase B, she asked P3 and I about *Rafigh*. She expressed interest when mushrooms started to become visible.
RQ2	P2	P2 referred to the mushrooms as "little ones" and "those guys".
RQ3	P2	P2 successfully described the relationship between *Rafigh* and her use of applications in the post-study interview.
RQ4	P2	
RQ5	P2	P2 checked the mushrooms in the mornings and when coming back from school. P2 requested to bring the harvested mushroom to the school to show to her friends.

RQ1	P3	According to P3, the mushrooms' growth rate was too slow to keep P2 interested.
RQ2	P3	P3 stated that the children wanted to show *Rafigh* to visitors and classmates. She stated that the children showed *Rafigh* to family and friends and wanted to show them to teachers and peers. She mentioned that the mushrooms' being real was novel and exciting for the children. In the post-study interview, she said the children were interested in the mushrooms' health. She believed interacting with other living beings could help children feel more responsible and caring.
RQ3	P3	P3 successfully described the relationship between *Rafigh* and P1 and P2's use of applications both after the initial explanation that I provided at the beginning of Phase B and in the post-study interview.
RQ4	P3	P3 expressed that she had conversations with P1 and P2 about nature and technology during the study that were triggered by the children using *Rafigh*. She believed that the children learned about nature and technology by using *Rafigh*. She stated that the children showed *Rafigh* to family and friend and wanted to show them to teachers and peers.
RQ5	P3	P3 believed the project was a valuable learning experience. She said, "it is good to have projects where children grow things". In the past, she had helped P1 and P2 grow other plants. According to P3, the mushrooms' growth rate was too slow to keep P2 interested. According to P3, P1 was interested in *Rafigh* during the study because he believed he was caring for the mushrooms. P3 believed that having *Rafigh* in the home created possibilities for discussion and conversation. At the conclusion of the study, P3 agreed to allow the children to bring the harvested mushrooms to their school.

Table 11. Qualitative data from Case Study 1

Relevant Research Question	Participant (s)	Statement/Observation/Action
RQ1	P4	P4 was interested in the tablet applications from the beginning of Phase A.
RQ2	P4	P4 started using target applications on the iPad from the beginning of the study but did not express interest in *Rafigh* at any point.
RQ3	P4	
RQ4	P4	
RQ5	P4	
RQ1	P5	P5 was interested in the mushrooms from the beginning of Phase B. He told P6 on more than one occasion that he had to use target applications so that the mushrooms would grow. He encouraged P4 to use the target applications more so that the mushrooms grow more. During Phase B, he checked the mushrooms everyday. He was still interested in the mushrooms 6 months after the study and asked P6 to get more mushroom kits to grow.
RQ2	P5	P5 was interested in the mushrooms from the beginning of Phase B to the end of the study. He told P6 several times during this time that he had to use applications so that the mushrooms would grow. He even encouraged his brother to use the iPad more so that the mushrooms would grow more. He checked them everyday. Even 6 months after the study, P5 was still interested in the mushrooms and wanted them to grow more. He had started to eat mushrooms after participating in the study.
RQ3	P5	According to P6, P5 grasped the relationship between *Rafigh* and his use of tablet applications. P6 had observed that P5 expressed that he had to collaborate with P4 in order for the mushrooms to grow.
RQ4	P5	P5 encouraged P4 to play more therapeutic games and collaborated with him in creating expressive stories.
RQ5	P5	During Phase B, P5 checked the mushrooms regularly, especially after school or in the mornings when the growth was more visible. At the end of the study, P5 wanted to grow the mushrooms again. He requested to bring

		the harvested mushroom to the school to show to his friends.
RQ1	P6	
RQ2	P6	P6 stated that the children wanted to show *Rafigh* to visitors and family. In the post-study interview, she stated that P5 was interested about the mushrooms' health and asked why they didn't grow larger. She believed that it was important that the mushrooms were real and that otherwise the children would have a different experience. P6 believed that using real mushrooms contributed to P5's interest in *Rafigh* and might have caused feelings of empathy in him.
RQ3	P6	P6 successfully described the relationship between *Rafigh* and P1 and P2's use of applications both after the initial explanation I provided at the beginning of Phase B and in the post-study interview.
RQ4	P6	P6 stated that *Rafigh* created opportunities for conversation about technology and mushrooms with the children.
RQ5	P6	P6 believed the project was a valuable learning experience for the children. She said the mushrooms created possibilities for dialogue and conversation between her and the children. She believed P5's interest in the mushrooms was linked to the fact that he believed he was caring for them. She encouraged the children to show *Rafigh* to visiting family and friends. At the end of the study, she agreed for them to harvest the mushrooms and bring them to school to show to their friends.

Table 12. Qualitative data from Case Study 2