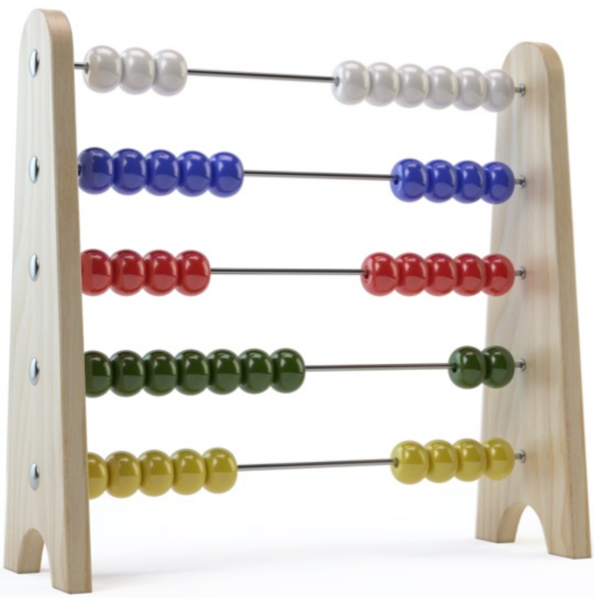
Child-Computer Interaction

Second Edition



Juan Pablo Hourcade

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By: Juan Pablo Hourcade

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Preface to Second Edition

It is difficult to believe that seven years have gone by since the first edition of *Child-Computer Interaction* came out. The experience with the experiment of self-publishing and making the book freely available in electronic format has been a positive one. I have received positive feedback from academics to software developers, which gave me the needed encouragement to work on this second edition.

The second edition incorporates child-computer interaction research from 2015 to 2020. Reading all of the new research was enlightening in understanding trends. There are positive ones, such as much greater attention paid to children with disabilities and neurodiverse children. Other trends have to do with technologies that have improved, such as robots and voice assistants.

This second edition, like the last one, was possible thanks to a Career Development Award, and an Obermann Center Fellowship, both from The University of Iowa. Together, they gave me one semester without teaching commitments and support for copy-editing the book.

Anna Egeland contributed by copy-editing the book; I am glad that she was available and able to help me once again with the book. Kerry Peterman added ideas for new illustrations.

All of the efforts in writing this second edition occurred during the COVID-19 pandemic, which means all the writing happened at home. Hence, my big thanks to my wife Silvia, my son Ben, and our dog Frosty for their patience and support as I worked on the book. I would also like to thank all my current and prior students for all the insight, feedback, and inspiration they have provided to me.

Iowa City, Iowa, April of 2022

Preface to First Edition

My first academic conference was CHI 99 (Human Factors in Computing Systems) in Pittsburgh. Back then there was a steady group of human-computer interaction researchers I would see at every talk about interactive technologies for children. The group got its own conference in 2002, when a workshop organized by Tilde Bekker and Panos Markopoulos in Eindhoven went so well that it turned into the Interaction Design and Children (IDC) Conference, which has enabled the building of the child-computer interaction community. This book is about the research of this community, focusing primarily on research published at the CHI and IDC conferences.

I wrote the book thinking of graduate students entering the field, but also thinking of practitioners and researchers coming from other fields who want to quickly catch up with child-computer interaction research. I also hope it can be a useful book for teaching courses on child-computer interaction. It is based on an earlier article I wrote for the journal *Foundations and Trends Human-Computer Interaction*, for which I was able to keep copyright.

The book is also a bit of an experiment in that I purposefully decided to self-publish, in order to make it accessible to a larger group of people. I also hope this arrangement will make it easier for me to make frequent updates to the book, making new versions available online. You, the reader, can also be part of this effort. If you notice any mistakes, or if you think something is missing from the book, please reach out to me at juanpablo-hourcade@uiowa.edu.

To ensure the quality of the book, I had the fortune of receiving the help of several members of the child-computer interaction community, who provided feedback on specific chapters. Mona

Leigh Guha provided feedback on Chapter 6, Lana Yarosh on Chapter 8, Meryl Alper on Chapter 9, and Narcís Parés on Chapter 11. I am very grateful for their help and support.

I was also fortunate to have Natasha Bullock-Rest as my copy editor. We have authored many publications together, and I could not think of anyone better to help me put the final touches to the book. I am thankful she made the time to do it. After Natasha finished copy editing, Anna Egeland worked on getting the material in publishable form for the printed and Kindle versions available through Amazon. As always, it was a pleasure working with her.

The book would not have been possible without a Career Development Award, and an Obermann Center Fellowship, both from the University of Iowa. Together, they gave me one semester without teaching commitments, as well as a wonderful location and great colleagues with whom to work as I wrote the book.

I also want to thank the people responsible for getting me into child-computer interaction, Allison Druin and Ben Bederson, who advised me during graduate school at the University of Maryland. Likewise, I am grateful to all my collaborators over the years, especially all the students who have worked with me at the University of Iowa, with special thanks to Keith Perry, Thomas Hansen, Natasha Bullock-Rest, Kelsey Huebner, and Elle Miller.

Finally, I would like to thank my parents, my wife Silvia, and my son Benji for their daily support and love.

About the Author

Juan Pablo Hourcade is an Associate Professor at The University of Iowa's Department of Computer Science and Director of Graduate Studies for the Interdisciplinary Graduate Program in Informatics. His main area of research is Human-Computer Interaction, with a focus on the design, implementation and evaluation of technologies that support creativity, collaboration, well-being, healthy development, and information access for a variety of users, including children and older adults.

Dr. Hourcade has held various leadership roles in his research community (e.g., Papers Co-Chair for CHI 2016 and CHI 2017, Co-Chair for IDC 2013). He is in the Editorial Board of *Interacting with Computers* and the *International Journal of Child-Computer Interaction*.

Content

Chapter 1
Introduction

What is child-computer interaction?

Child-computer interaction concerns the study of the design, evaluation, and implementation of interactive computer systems for children, and the wider impact of technology on children and society. This definition, paraphrasing the Association for Computing Machinery's (ACM) definition of human-computer interaction, lists design, evaluation, and implementation in an order in which they normally do not occur. This order is intentional, as most human- and child-computer interaction research is about design, followed by evaluation, followed by implementation.

Child-computer interaction is gaining in importance as computers increasingly play a ubiquitous role in our lives, including the lives of children. Children in high-income regions of the world are now growing up expecting items they encounter to be interactive and content of their choice to be immediately available. It is likely that children in low-income regions will experience the same even before they have access to basic services such as sanitation.

As children grow up using interactive computer devices more frequently, the way they learn, play, and interact with others is changing. Whether the changes that occur are positive or negative will depend on how these interactions with computers are designed and how these devices are used. Child-computer interaction is the field that studies how to design interactive technology for children and how children may make the most out of it in order to have the most positive impact on their development.

How is child-computer interaction different from adult-computer interaction? Read and Bekker (2011) suggested the following key differences: the rate of change of children when compared to adults, the frequent involvement of adults in children's interactions with technology (the opposite is not true), the different contexts of use, and the underlying cultural and societal values with regard to what is good for children (J. C. Read & Bekker, 2011).

A brief history of the field

As computers rose to prominence after World War II, their use centered on military, business, and scientific applications. In the 1960s and 1970s, a group of pioneering researchers at the Massachusetts Institute of Technology began exploring the design of computer systems for children. Their original focus was making computer programming accessible to children, but in the long term, their work had broad influences, including early tablet and laptop design ideas, the development of object-oriented programming, and a vision for the use of computers in education (Kay & Goldberg, 1977; Papert, 1993).

These pioneers were not alone in their interest in expanding the use of computers to a wider audience. An interdisciplinary group of researchers including computer scientists, psychologists, and engineers slowly began forming what is now known as the human-computer interaction field, focusing on methods for design, implementation, and evaluation of interactive computing systems. Encouraged by the release of *IBM's Personal Computer* in 1981, they began organizing the Human Factors in Computing Systems (CHI) conference 1982, beginning as an official Association for Computing Machinery (ACM) conference in 1983.

After sprinkles of work influenced by both traditions in the 1980s, a steadier flow of research in child-computer interaction began in the 1990s, with growing influences from education, developmental psychology, graphic design, and communication studies. This movement coalesced with the first Interaction Design and Children (IDC) conference, organized in 2002. Since then, this annual conference has been the center for child-computer interaction research. While its foundation came largely from the human-computer interaction field, over the years it has incorporated work from researchers who typically publish in education and media studies venues. A few articles have analyzed trends at the conference (Kawas, Yuan, et al., 2020; Van Mechelen et al., 2020; Yarosh et al., 2011).

The 10 pillars of child-computer interaction

As the child-computer interaction field matures, some guidelines for success have emerged, some well-established in the field, others still in their nascent stage. They provide lessons on how and what to design.

Work in interdisciplinary teams

These days, interactive technologies for children are most often created by design teams instead of individuals. The most successful projects tend to have interdisciplinary teams, or at the very least, involve people experienced in design and evaluation methods, technology builders (e.g., computer scientists, engineers), and experts in the particular child population being targeted (e.g., children, parents, teachers, psychologists, educators). In addition, most teams include a designer (graphic or industrial), and experts in the topics the technology touches (e.g., if it is digital library software, a librarian).

Deeply engage with stakeholders

The design process to create an interactive computer system involves a series of steps, from setting requirements, to establishing designs, to implementing and evaluating technologies. Deeply engaging with key stakeholders during the design process significantly increases the chances that a technology will be successful and ethical. As adults, not only do we have difficulty remembering what it was like to be children, but we have to realize that each generation of children has its own views, expectations, and experience with technology, as well as its own needs and interests. For this reason, it is important to involve children throughout the design process. Just like human-computer interaction researchers and practitioners call for user-centered design, in the child-computer interaction field, we value child-centered design.

Children are not the only ones affected by the technologies they use; caregivers and other adults with whom children interact, such as teachers, should also play a role in the design process. Likewise, it is often not sufficient to meet stakeholders; there is also a need to learn about their daily realities and the contexts in which technologies are likely to be used.

Involving all stakeholders and ensuring that they have a strong voice in design decisions, in particular with respect to data collection, privacy, and user modeling issues, can also go a long way in making it more likely that projects will have ethical outcomes.

As a rule of thumb, the less familiar the design team is with the stakeholders and the contexts in which they will use technology, the more deeply it should engage with them. An overview of design and evaluation methods that can be used to facilitate this engagement is provided in Chapter 6.

Evaluate impact over time

Children usually do not change immediately when they use technology. In fact, skills and abilities emerge over time (see Chapter 2 under *Computationally and biologically-inspired theories*), so to truly understand the impact of technology we need to see how it affects children over an extended period. Out of the ten pillars of child-computer interaction, this is the one that is currently implemented the least, mostly due to limited budgets to evaluate technologies.

Design the ecology, not just the technology

Technology use is significantly affected by context. For this reason, when designing technologies for children, it is important to not just think of the technology, but to take into account the broader context of use. In addition, design teams can go further and design the whole ecology of use. In other words, do not stop at the technology, but instead design the physical space where it will be used, and perhaps even think about the people who may be present when the technology is used, and the supportive activities. For more information on this approach see Chapter 6 and its section titled *Ecological approaches*.

Make it practical for children's reality

For a technology designed for children to be successful, it needs to be able to work in children's real contexts. While it is often necessary to start the design process in a lab, designs should consider, from the beginning, the contexts in which children are likely to use a technology, and whether it is a good fit for these contexts. Fragile, heavy, uncomfortable, flimsy, or dangerous designs are unlikely to make an impact. Likewise, technologies should be relevant to children's lives, needs, and interests.

Personalize

Children arrive at the use of technologies having gone through different life experiences, with a different set of skills, neural structures, and bodies. Their needs and interests are diverse. They vary in their range of abilities. For this reason, personalization can provide great benefits in making technology advantageous for children. It is important to point out that this is even more important for children than for adults, as younger children are more likely to show greater diversity in needs and abilities when compared to older children and adults. At the same time, personalization should not get in the way of children experiencing activities together.

Be mindful of skill hierarchies

In many domains, including music and education, the learning process consists of learning basic skills, and then adding more complex skills that are based on the first set. Design teams need to be mindful of the skills necessary for using an interactive technology, and ensure that the children who will use the technology have those basic skills. If children are learning skills through technology, then again, skill hierarchies should be noted. For more information see section on *Behaviorism* under Chapter 2.

Support creativity

Learning can be more motivating if it is done with a purpose meaningful to the child, such as creating or building. This idea forms the basis of the concept of *constructionism*, which has had great influence on the field of child-computer interaction (more on this in Chapter 2). *Constructionism* has influenced the push to enable children to program computers with outcomes they can relate to, whether it is drawings in the *Logo* programming language or robots made out of *LEGO* bricks with *LEGO Mindstorms*. This focus has been greatly expanded in the child-computing interaction community with interactive technologies now supporting a wide variety of other creative activities including storytelling, music authoring, three-dimensional design, smart textiles, and so forth (see Chapter 7 for examples).

Augment human connections

Secure attachments to primary caregivers are paramount to children's positive development. Likewise, face-to-face interactions with teachers, friends, and other peers are a foundation for the learning and development of critical skills, such as listening, negotiating, sharing, teaching, and helping others. Read more about the importance of human connections in Chapter 2 under *Sociocultural approaches*.

While computers can often interfere with these personal connections, they can also augment them. Within child-computer interaction, there has been a significant amount of attention paid to communication and collaboration technologies, with many including support for face-to-face collaboration most recently through touchscreen, tangible, and full-body user interfaces. There has also been research on technologies to support remote communication, mostly with the aim of keeping children in contact with close family. See Chapter 8 for more examples of research in this area.

Enable open-ended, physical play

Children who participate in open-ended, physical play can benefit in many ways, including having better health, developing problem-solving skills and resiliency, learning to engage with peers, negotiating, and advocating for themselves (read more in Chapter 2). The child-computer interaction community has worked on supporting this form of play, with many examples of computer-enhanced indoor and outdoor physical play in Chapter 11 under *Promoting healthy lifestyles*.

Overview of the book

The rest of the book is divided in four sections. The first section provides background on children's development and the risks and opportunities associated with technologies. Chapter 2 covers child development and discusses the best-known theories and concepts from developmental psychology and how they apply to child-computer interaction. Chapter 3 discusses the risks that technology may bring children and how to avoid them.

The following section provides more background on basic concepts from human-computer interaction and how they apply to child-computer interaction. Chapter 4 defines usability for children, including a discussion of user experience and usability goals. Chapter 5 provides an overview of usability principles and heuristics by revisiting guidelines for adults from a child's perspective. Chapter 6 is an introduction to design and evaluation methods that includes a review of lifecycle models, an overview of methods based on children's roles, followed by more detailed examples of activities that can be conducted at each step of the design process.

The next section is a literature review of research in child-computer interaction, organized by topic. Chapter 7 presents research on creativity and problem solving, including programming, storytelling technologies, and "maker movement" enabling technologies. Chapter 8 includes research on collaboration and communication, including a discussion of technologies to support face-to-face activities, as well as those designed to support remote communication. Chapter 9 is about accessing media and includes research on search engines, digital libraries, and interacting with digital content. Chapter 10's topic is learning, including a review of research on interactive technologies designed for children to learn science, mathematics, reading, writing, and other topics. It also includes a discussion of overall strategies for the design of learning applications and the challenges of bringing computers to schools. Chapter 11 covers research on technologies to promote health, and to help neurodiverse children, children with disabilities, and marginalized children. These include technologies to promote healthy lifestyles, assist children with specific health conditions (e.g., diabetes), and support children with disabilities (e.g., children with motor impairments).

The last section of the book consists only of Chapter 12, which is a look at the future of child-computer interaction. It includes a discussion of possible risks ahead, remedies for these risks, as well as research challenges for the child-computer interaction community to grow as a field and make a stronger, more positive impact on society.

Summary

Child-computer interaction concerns the study of the design, evaluation, and implementation of interactive computer systems for children, and major phenomena surrounding these elements. As children grow up using interactive computer devices more frequently, the way they learn, play, and interact with others is changing. Whether the changes that occur are positive or negative will depend on how these interactions with computers are designed, and how these devices are used. Child-computer interaction is the field focused on how to design interactive technology for children, and how children may make the most out of it in order to have the most positive impact on their development.

Child-computer interaction rose out of the work on making computer programming accessible to children and the field of human-computer interaction. It has since counted significant contributions from other fields including education, developmental psychology, and media studies. Since 2002, the annual Interaction Design and Children (IDC) conference has been the epicenter of child-computer interaction research.

As the field has matured, specific approaches have emerged as best practices. These constitute the ten pillars of child-computer interaction: work in interdisciplinary teams, deeply engage with stakeholders, evaluate impact over time, design the ecology not just the technology, make it practical for children's reality, personalize, be mindful of skill hierarchies, support creativity, augment human connections, and enable open-ended, physical play.

Chapter 2
Child Development

To understand how to best design technology for children, we must first consider existing research on child development. Child development is a dramatic, highly-complex process that we are only beginning to understand. For example, children typically acquire more than 60,000 words in their first 18 years of life (Bloom, 2002), each with its own sound pattern, spelling, and meaning. Children also rapidly improve in motor abilities, and (when given the opportunity) are often able to handwrite, type, and play a musical instrument by the time they complete elementary school (Klinedinst, 1991; Nichols, 1996). These improvements are also reflected in children's ability to use input devices (Hourcade, Bederson, Druin, et al., 2004; Hourcade et al., 2015; Vatavu, Cramariuc, et al., 2015). Other cognitive improvements are exemplified by Kail's model of changes in reaction times and information processing speed (Kail, 2000). This rapid pace of development is accompanied by a high amount of within- and between-child variability (Siegler, 2007). This high rate of change and high variability is one of the key differences between children and adults that need to be taken into account when designing interactive technologies (J. C. Read & Bekker, 2011).

Living organisms, including children, develop through bidirectional interactions that go from genetic activity, to neural activity, to behavior, to the environment, and back (see Figure 1) (Gottlieb, 1991). The greater the flexibility at each layer, the more adaptable children's development. The place where computers play a role is in mediating (together with the body) the interactions between behavior and environment. Indeed, computers are arguably the most flexible, malleable, and powerful tools people have ever had available.

To understand how to best influence these developmental changes, designers need to consider the child development literature to make it more likely that children can change in healthy ways while using technologies, and that these technologies are appropriate for children's needs, abilities, and interests.

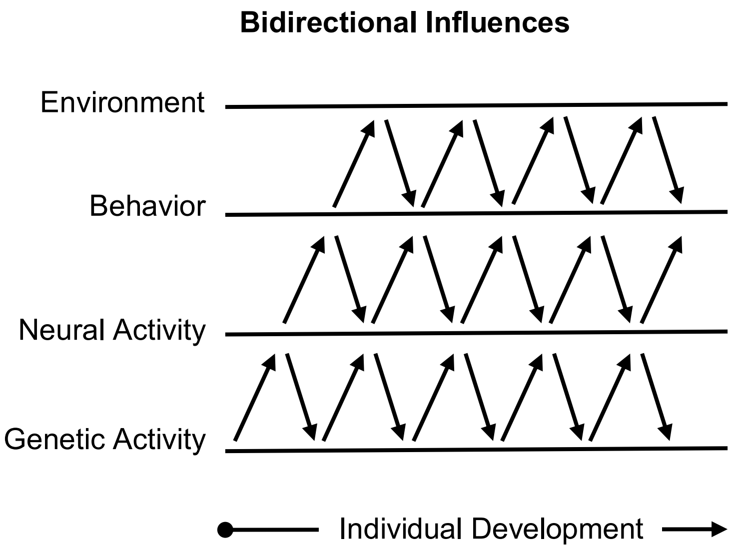

Figure 1. Bidirectional influences on development (Gottlieb, 1991).

This chapter provides an overview of the child development literature while focusing on aspects that matter to the design of technology. It begins with theories of development that have had a significant impact on the field of child-computer interaction, including constructivism and its extension constructionism, and sociocultural theories inspired by Vygotsky's ideas. Both of these approaches provide the foundations for more recent theories, such as neuroconstructivism, connectionism, and dynamic state theories that provide stronger connections to the biology of the brain.

The chapter continues with a discussion on theories of intelligence and how to measure it, as well as of skills, such as executive function and emotional intelligence, that can help improve performance in school and on intelligence tests.

Constructivism

Jean Piaget was arguably among the most influential experts on child development during the 20th century. His work continues to have a significant influence on developmental psychology and educational research, while his views on how children learn have also affected the field of child-computer interaction.

Below, three aspects of Piaget's work are highlighted: how children construct knowledge through a process he called adaptation; the role of maturation, experience, social aspects, and emotional aspects in children's development; and the developmental stages children go through as they develop.

Adaptation, constructivism, and constructionism

Piaget thought that learning occurs through a process of adaptation, in which children adapt to their environment. He saw this adaptation as an active process in which children construct knowledge structures by experiencing the world and interacting with it.

This idea, referred to as *constructivism*, holds that children actively construct their own knowledge through experiences. The same experience will affect individual children in different ways, since they will come to it with different existing knowledge structures (Piaget & Inhelder, 1969). This view stands in contrast with the idea that children simply store knowledge imparted by others and all perceive and learn from an experience in the same way. The basic Piagetian view of development is more consistent with recent theories of child development, including neuroconstructivism, dynamic systems theories, and connectionism, than is the passive view (Mareschal et al., 2007; Schöner, 2009; Thelen & Bates, 2003).

Seymour Papert, a key figure in the genesis of the field of child-computer interaction, expanded on Piaget's ideas with his proposal for *constructionism*. Papert proposed that Piaget's adaptation works best when children are "consciously engaged in constructing a public entity" (Papert & Harel, 1991). In other words, making something to share with others helps children construct knowledge. Papert extended Piaget's concept of adaptation by placing a greater emphasis on the social and motivational aspects of learning, as well as on the importance of providing children with more opportunities to modify their environment, instead of just experiencing it.

Papert's ideas have had a great influence on the field of child-computer interaction. This influence is particularly clear in the emphasis on providing children with technologies with which they get to be authors, rather than experiencing worlds and situations that are pre-scripted, or absorbing facts provided by a computer. His influence is also apparent in the recurring focus on having children participate in designing the technologies that they use. In great part, Papert's interest in computers for learning arose from the wide variety and complexity of entities children can construct using computers, which thus provide better learning opportunities and empower a shift from learning by being told to learning by doing. Papert also saw computers as a way of helping children connect their interests with subjects they may not otherwise enjoy (Kestenbaum, 2005).

Factors affecting development

Piaget cited four major factors that he thought affected development: maturation, experience, social aspects, and emotions. All four have a direct impact on how technologies for children should be designed. In the case of maturation, being aware of what most children are able to accomplish at a given age can provide interaction designers with useful guidelines. The other three factors are crucial in the design of educational technologies that can provide children with new experiences where they can interact with others as part of activities of interest (Piaget & Inhelder, 1969).

Children's physical maturation limits what and how they are able to learn. Piaget thought that while maturation certainly plays a role in learning, it does not guarantee that learning will occur. Rather, it limits what children can do (Piaget & Inhelder, 1969). As children grow up, their potential for learning increases. Hence, children's limited cognitive and motor abilities will limit their ability to interact with technologies. This view on maturation needs to be taken in context of evidence that maturation, and in particular cognitive development, is affected by the environment in which children grow (Gottlieb, 1991; Quartz & Sejnowski, 1997). In other words, while children's maturation limits what they can do, the experiences they go through shape neural development and thus affect how they change as they grow up.

Piaget viewed experience as a key factor in adaptation. Experiences are required for building knowledge structures (Piaget & Inhelder, 1969). This emphasis on experience underlines the importance of learning about the world by experiencing it rather than being told about it, as Maria Montessori stressed (Montessori, 1964). Technologies can provide unprecedented experiences through their great malleability, enabling children to modify their environments and experience them in ways that were not previously possible.

Piaget thought that social interaction played a crucial role in development by enabling knowledge to be passed from one generation to the next (Piaget & Inhelder, 1969). The core of the contributions to this topic comes from sociocultural approaches to development that were pioneered by Lev Vygotsky (Vygotsky, 1978). We discuss these under *Sociocultural approaches* below. One important aspect of social interaction in development is that the knowledge that gets passed from one generation to the next is not just information, but strategies. In a panel at the IDC 2004 conference, Turing Award recipient Alan Kay made an interesting point when mentioning that when teachers assign something such as a composition and they do not do it themselves, they are indirectly telling children that it is not interesting (Kestenbaum, 2005). Computers can help in this respect by making links between passionate interests and powerful ideas not only for children, but also for the adults that play a role in children's education.

Piaget also highlighted the role that motivation and emotions play in development. He said that children's motivations to learn are in great part due to their drive to grow, love and be loved, and assert themselves (Piaget & Inhelder, 1969). Motivation can be achieved by making learning activities relevant to children's lives and interests as recommended by other pioneers, such as Dewey, Montessori, and Vygotsky (Dewey, 1959; Montessori, 1964; Vygotsky, 1978). Papert went a step further and made a distinction between activities that are relevant to children's lives and those that children feel passionate about. He believed the latter would be much better at motivating learning (Kestenbaum, 2005). This view highlights the need for providing children with learning opportunities that are flexible or varied enough to help every child find something that speaks to their interests. Motivation is an area where computers can prove to be a positive tool due to their flexibility in providing a variety of experiences and learning opportunities.

More specifically, researchers have taken into account Piaget's views on motivation when providing children with technologies that incorporate learning in entertaining ways. Games are increasingly used for teaching a variety of subjects, and are particularly popular in commercial mathematics learning software for children. Fisch provides an overview of basic guidelines to follow when incorporating learning into games (Fisch, 2005). Storytelling is another approach that can make learning more interesting for children. It is often what brings together the games used for learning, but could also be used without a game component (Bonsignore et al., 2013; Cassell, 2004; Hourcade, Bederson, & Druin, 2004b; Hourcade, Bullock-Rest, et al., 2012; Kelleher et al., 2007; Rubegni & Landoni, 2014).

Developmental stages

Arguably, Piaget's best known and most critiqued contribution is his idea of developmental stages. He proposed that all children go through a series of stages in their development on their way to attaining logical, analytical, and scientific thinking. At each stage, children present typical behaviors and are limited in the types of mental operations they conduct. Piaget argued that all children go through the stages in the same order, and none of the stages may be skipped. He proposed age spans for each of the stages but acknowledged that different children go through the stages at different speeds and thus reach stages at different ages (Piaget, 1973; Piaget & Inhelder, 1969). The four stages include the sensory-motor stage (0-2-year-old children), the preoperational stage (2-7-year-old children), the concrete operations stage (7-11-year-old children), and the formal operations stage (11-16-year-old children). Piaget's descriptions of each stage are useful in identifying why children may have difficulty with a particular type of interaction.

Developmental aspects can have an impact on the design of technologies, starting with the preoperational stage. Preoperational children (2-7-year-old children) are egocentric, meaning they see the world only from their own perspective, and have great difficulty seeing from someone else's point of view (Piaget, 2002a, 2002b). This egocentrism can be seen in the difficulty of partnering with children in this age group in the design of technologies (Guha et al., 2004). Children in the concrete operations stage (7-11-year-old children) are more likely to appreciate someone else's perspective, which enables them to better work in teams and as design partners with adults. Preoperational children also tend to concentrate on only one characteristic of an object at a time, a limitation that extends to understanding hierarchies (Piaget, 2002a, 2002b). This limitation on hierarchies is one important lesson to remember when designing technologies for this age group: interfaces that require navigation through hierarchies should be avoided and alternatives should be provided. Concrete operational children, on the other hand, are able to understand hierarchies and reverse actions in their head, which can enable them to use a greater variety of technologies and software (Piaget, 1957). More abstract concepts, such as using deductive reasoning and logically analyzing options tend to appear more consistently during the formal operations stage (11-16-year-old children). More details on how children's problem-solving abilities evolve can be found in Appendix A.

The idea of developmental stages has been criticized. One of the main criticisms questions the assertion that children will behave consistently on tasks given their developmental stage. Rather, research has indicated that a child's developmental stage only produces a likelihood that a child will behave in a particular way (Flavell et al., 2002). Children's performance on tasks also depends on several factors, such as the amount of information in a task, social support, and instructions. For example, the amount of information in a task can affect performance because larger amounts are more difficult to handle by a limited working memory. Hence children's working memory capacity can be a confounding variable. Recent research taking these factors into account has provided evidence that children and infants are more competent than Piaget thought, while older children and adults appear to be less competent (Flavell et al., 2002).

Another area where Piaget's developmental stages fall short is in addressing the role that social and cultural factors play in children's learning and performance in tasks. These issues are explored below under *Sociocultural approaches*. Similarly, there has been criticism of Piaget's consideration of logical-analytical thinking as the highest form of intellectual development. Gardner's multiple intelligences theory proposes that there are other types of intelligences, which is explained under the section on *Multiple intelligences* in this chapter. Sternberg's successful intelligence theory takes a practical and inclusive approach in defining intelligence and is described under the *Successful intelligence* section, also in this chapter.

It is still advantageous to know about the typical needs and abilities of children at specific ages, as this knowledge can provide rough guidelines for what may and may not work when designing interactive technologies. Appendix A presents a detailed overview of child development in terms of perception, memory, problem solving, language, and motor skills.

Sociocultural approaches

The work of Lev Vygotsky, a Russian psychologist who conducted his research early in the 20th century, but whose work did not become widely known until the 1970s, has been quite influential in highlighting the importance of social aspects in child development. Vygotsky thought that language, signs, and tools play a crucial role in cognitive processes. For example, he thought children learn to plan actions by using speech, which later turns into the inner speech of adults. He also saw writing and more generally the use of external tools and signs as ways of augmenting human cognition. As an extension to this concept, he saw learning as social in nature, observing that children are able to complete tasks with some help from adults or older children before they can complete them on their own. In making this observation, he stressed appropriate social supports as being critical for children's learning (Vygotsky, 1978).

Out of Vygotsky's ideas come some concepts that are often cited in the child-computer interaction and the learning sciences literatures. One is the concept of *scaffolding*, which refers to the help children require to complete a task before they can complete it on their own (D. Wood et al., 1976). Once children internalize the process that helps them accomplish a task, they are able to complete the process individually. Some research on children's technologies refers to the technologies providing the scaffolding, instead of teachers or parents (Soloway et al., 1996). When children can complete a task with scaffolding, but cannot complete it on their own, they are in the *zone of proximal development* (Vygotsky, 1978). Vygotsky thought that the most appropriate time for children to learn is when they are in this zone, rather than when they are ready to complete tasks individually. He also thought that challenging children while providing social supports would help children learn material more quickly.

Many other researchers have followed in the footsteps of Vygotsky, forming what today are referred to as sociocultural approaches to learning. In these approaches or theories, children's learning is seen as an active process of interactions with other people and tools; children are not passive recipients of knowledge (see Figure 2). Knowledge is not seen as constructed individually in the mind, but socially in the world. These approaches study learning in a given sociocultural context instead of studying individual children in isolation, and study children's cognition as it connects with society.

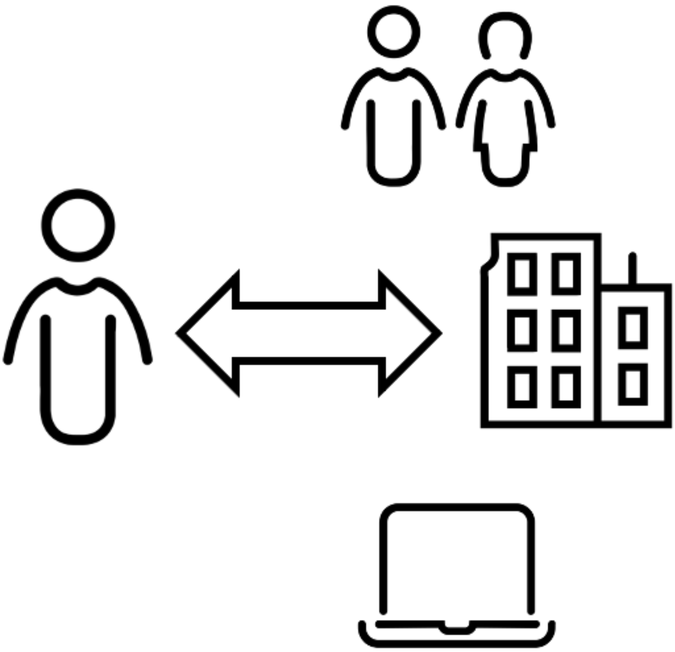

Figure 2. In sociocultural approaches, learning is seen as an active process involving interactions with other people, the environment, and tools (including computers). Icons by Delwar Hossain from the Noun Project.

There are two levels at which the sociocultural context can be studied. One is the overall society and culture to which the child belongs. Researchers have pointed out that in different parts of the world, different kinds of knowledge and skills are valued. Similar claims can be made for different times in history. Thus, cognitive development will always be seen through the lens of a particular sociocultural context. The second level at which sociocultural context can be studied is in the immediate vicinity of the child: how family and school environments provide learning opportunities and scaffolds. Different family and school values will lead children to different routes in cognitive development (Flavell et al., 2002). In many ways, the sociocultural approach to learning goes back to the notion of an apprenticeship, similar to that in middle age guilds and to what occurs in graduate schools between students and their advisors.

One example of sociocultural approaches is situated learning or situativity theory. This approach sees learning as occurring in activities where children interact with their environment as well as with adults and other children (J. S. Brown et al., 1989; Chaiklin & Lave, 1996; Greeno & Middle School Mathematics through Applications Project Group, 1998; Lave et al., 1991). Knowledge is not seen as belonging solely to individuals, but rather as being distributed between them and the tools, artifacts, and other people in their environment. The interactions between individuals and the environment transform both. Thus, these situations are studied rather than the individuals in them. These theories, as well as those in similar areas such as social constructivism, have led to instructional methods where context is seen as an integral part of learning, rather than simply influencing individual cognition (A. L. Brown & Campione, 1996; Cobb & Yackel, 1996).

These social approaches and instructional methods appear in contrast to much of the current use of personal computers in education. In the United States, for example, typical use of computers in schools is largely individual, with children often wearing headphones that tether them to their computers. These setups significantly limit the potential for social interactions. There is a need to consider uses of technology that can enable children to better connect with their social and physical environments (Hourcade et al., 2017).

Attachment

Children's attachment to primary caregivers (mostly parents) has a prominent role in the view of child development in fields such as psychiatry and social work. Attachment is a fundamental need for children, rooted in a biological basis. It helps children feel secure, regulate their emotions, learn to communicate, relate socially, self-reflect, and experience confidence in exploring the world. Secure attachments occur when primary caregivers are consistently responsive, emotionally available, and loving. When children do not have secure attachments with a primary caregiver, they are more likely to show higher levels of hostility and negative interactions with other children, less autonomous behavior, low self-confidence, and poor academic performance (Siegel, 2020). While this book focuses on designing technologies for children, if we want to help children's development, especially early in life, we have to consider how technologies for adults affect the level and quality of attention they pay to the children in their care in order to promote secure attachment.

Literacy environment

The family environment can play a significant role in children's development. For example, studies point at higher language and cognitive skills for children with access to richer literacy environments. These include literacy activities (e.g., shared book reading), the quality of participation on the part of primary caregivers (e.g., quantity and style of speech), and access and exposure to appropriate learning materials (e.g., books, toys that enable symbolic play) (Rodriguez et al., 2009). Interactive technologies can play a positive role in shaping the family environment, especially in providing opportunities for shared literacy activities and promoting availability of appropriate learning materials.

Play

Play is increasingly considered to have a crucial role in development. There is evidence that it contributes in many physical and cognitive ways, including preventing obesity (Goran et al., 1999), promoting learning and problem-solving skills (Bergen, 2002; Ramani & Brownell, 2014), and creativity (Mullineaux & Dilalla, 2009). The connections to developing social and emotional ties are even more obvious, with play promoting greater social engagement in a pleasant context, enabling children to develop negotiation and self-advocacy skills. Facing challenges as part of play can help children develop resiliency, and can also enable them to "act" in an older, more responsible fashion (Milteer et al., 2012). Vygotsky was also a strong proponent of play's role in development, favoring role-play to help children learn to regulate their behavior and the symbolic use of physical items in order to develop abstract thinking (Vygotsky, 1967). The challenge for technology design is to enable play with computers to retain the positives of traditional play, including physical activity, rich social interactions, and open-ended possibilities.

Computationally and biologically-inspired theories

Computationally and biologically inspired theories, such as neuroconstructivism, dynamic systems theories, and connectionism, have developed within psychology, building on Piagetian and sociocultural approaches. Their proponents' goal is to understand how developmental changes occur over time, as opposed to understanding what develops when and under what conditions. To accomplish this goal, these approaches make use of mathematical and computational models. They also attempt to bridge knowledge of the biology of the brain with the higher-level concepts used in traditional cognitive development theories. Finally, because of the use of models, these theories can be tested through empirical studies, where predictions can be made about how developmental change occurs (Mareschal et al., 2007; Oakes et al., 2009; Schöner, 2009; Thelen & Bates, 2003).

Computationally and biologically inspired theories make a strong emphasis on *embodiment*, also referred to as *situatedness*. They see development as occurring through bidirectional interactions between the brain, the body, and the environment (including other people) (see Figure 3). In particular, the view is that knowledge structures or representations are not independent of the body or the environment, and are only sufficient for a specific context. The problems that prompt developmental changes occur in the body and the environment, and the body and environment are used to solve them. Not only that, but as change occurs, the brain, the body, and the environment change together (L. B. Smith, 2005).

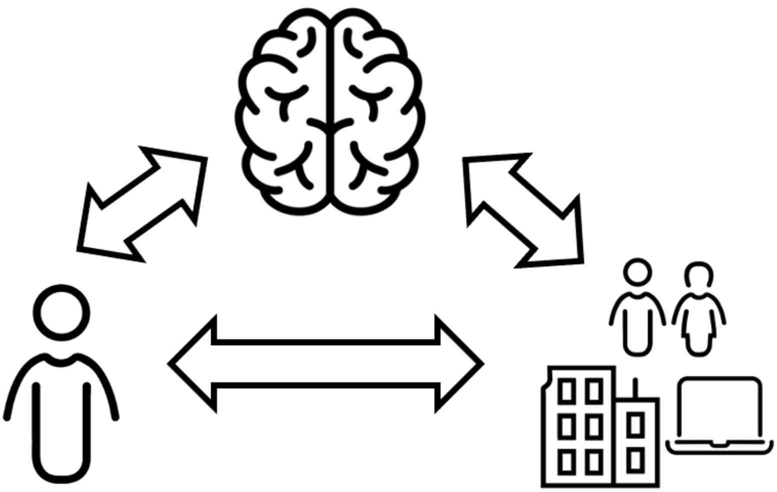

Figure 3. Embodiment sees development as occurring through bidirectional interactions between the brain, the body, and the environment (including other people and tools). Icons by Delwar Hossain and Arief Mochjiyat from the Noun Project.

The concept of embodiment has seen increased interest in the past 15 years within the field of child-computer interaction (A. N. Antle, 2013). This interest has been brought about by an awareness of recent approaches to child development like those described in this section. It has also been prompted by the greater availability of technologies that make it possible for children to interact with a computer by using their whole bodies (e.g., Microsoft Kinect), and to use computing devices in a wide variety of environments (e.g., smartphones). The concept of embodiment also implies that the context in which technologies are designed and evaluated is likely to have a significant impact on design and evaluation outcomes.

The dynamic nature of the environment means that knowledge structures, representations, and behaviors are constantly emerging to respond to changing contexts. These theories have a specific interest in how *emergence* occurs as a consequence of the interactions between brain, body, and environment. In particular, the theories suggest that cognition and complex forms of behavior emerge in suitable environments. They also suggest that the emergence of skills, behaviors, and so forth is due to diverse processes that unfold over time (Schöner, 2009).

These computationally and biologically inspired theories also incorporate the concepts of plasticity and variability. *Plasticity* refers to the ability of nervous systems, including the brain, to dynamically change in reaction to experiences and the environment (Anderson et al., 2011). It occurs through changes in neuronal network organization. Some of these changes are directly tied to development, and are thus more likely to occur during childhood and adolescence (Spear, 2013), while the changes that require the modification of existing neuronal networks can occur at any point in human life (Kolb & Gibb, 2014).

The computational models these theories use are stochastic, meaning that the outcomes of a particular combination of brain, body, and environment are not deterministic, but probabilistic. In other words, given the same conditions, the same child may behave differently. This explains within-child *variability*, which could of course be substantially increased by changes in the environment. As plasticity decreases and knowledge structures and behaviors become more specialized, variability also decreases, with more consistent behaviors likely to be observed (Spencer & Schöner, 2003).

Siegler and others have identified the issue of high variability in cognitive task performance within as well as between children. They have observed that children will choose from a variety of strategies and will not follow the same strategy consistently as would be suggested by Piaget's stages of development. For example, in a study asking toddlers to reach for a toy, Chen and Siegler found that 74 percent used at least three different strategies (Z. Chen & Siegler, 2000). Not only that, but children who show greater cognitive variability are likely to fare better in learning (Siegler, 2007). Another cause for variability is that children may take some time before they can apply a strategy to a variety of tasks (Z. Chen & Siegler, 2000).

Implications of emergence, plasticity, and variability

The concepts of emergence, plasticity, and variability have several implications when it comes to designing technologies for children. First is that the use of technologies needs to be studied over time, and while quick sessions may uncover usability issues, only long-term use will help us understand what developmental changes occur when a technology is introduced in a child's environment. The second is that technologies are likely to have a greater impact on younger children due to their greater plasticity. This means that extra care should be devoted to ensure that the use of technologies has positive developmental effects on young children, especially as ages of first use continue to go down. Finally, to account for variability, any design and evaluation activities for younger children should ideally include more participants (due to greater variability) than would be necessary for older ages.

Other theories

Privileged-domain theories

Privileged-domain theories consider the mind to be domain-specific, with specialized structures that are interconnected. Part of the evidence behind these theories comes from neuroscience and its study of brain activity showing certain parts of the brain to be most often dedicated to certain types of cognitive tasks. In addition, there is evidence that the brain can adapt to uncommon circumstances, reusing parts of the brain for purposes for which they may not typically be used (e.g., deaf children using parts of the brain normally dedicated to auditory processing for visual processing purposes instead). Some theorists also propose that children are born with learning mechanisms tuned to cognitive tasks that are particularly important for humans, such as acquiring language, recognizing faces, perceiving objects, and discriminating between living and non-living things. These mechanisms may explain why children learn very rapidly in some domains (Z. Chen & Siegler, 2000; Flavell et al., 2002).

Behaviorism

Behaviorism studies learning from the perspective of observing and measuring behaviors as a response to stimuli. It ignores what happens in the brain and treats it as a black box. Skinner saw learners as acting on the environment and receiving feedback on their behavior (Skinner, 1968) (see Figure 4). Learning a behavior given a set of stimuli is achieved through feedback: positive reinforcement, where the learner receives something they want (e.g., a good grade), and negative reinforcement, where the learner is rewarded by escaping or avoiding something they do not want (e.g., taking a final exam). Feedback to discourage undesired behaviors and help learners distinguish them from desired behaviors is accomplished through punishment, such as taking away something the learner wants, or giving them something they do not want (e.g., a low grade). Skinner also developed the concept of shaping, wherein a complex task is taught by breaking it up into smaller ones and providing reinforcement for segments of behavior (Skinner, 1968).

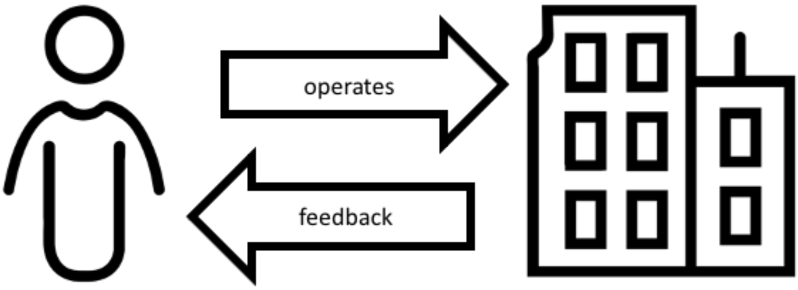

Figure 4. Behaviorism sees learners operating or acting in the environment and receiving feedback from it. Icons by Delwar Hossain from the Noun Project.

Behaviorism puts emphasis on drills and practicing where learners remember and respond (Hung, 2001). It can be helpful for situations where automatic responses are useful or necessary, for example, remembering multiplication tables, playing a musical instrument, spelling, and typing. These behaviorist strategies have been used in educational games. Behaviorism has also been useful in the design of interventions for neurodiverse children, such as children diagnosed with autism (Sundberg & Michael, 2001; Venkatesh et al., 2013).

Behaviorist approaches can complement approaches that focus on higher cognitive processes by providing the building blocks necessary for completing more complex tasks. With the task of writing, for example, behaviorist approaches can help children develop basic handwriting skills, while constructionist approaches can lead children to collaborative storytelling activities. Problems can occur if behaviorist approaches are used to involve children in higher-level cognitive activities such as storytelling, or if constructionist approaches are used to teach low-level skills such as handwriting. In the case of teaching low-level skills though, a combination of both approaches could be advantageous (e.g., getting practice while participating in making something of interest).

Skills and intelligence

Education systems in many regions of the world, including the

United States, are increasingly relying on testing and quantitative measures to demonstrate the educational effectiveness of pedagogical approaches, including the use of technologies. Hence, it is important to be aware of the leading theories of intelligence and how tests attempt to measure intelligence. It is also important to learn about factors that may have a significant effect on academic performance and social wellbeing, such as executive function and emotional intelligence.

Psychometric theories

Psychometric theories make use of tests to assess and predict the intelligence of individuals, including children. These theories vary in the number of factors believed to influence intelligence. Some like Spearman, proposed one general factor, called (g), while Thurstone proposed seven factors, and Guilford 180 factors (Z. Chen & Siegler, 2000). More recently, Carroll developed a hierarchical theory with (g) at the top, followed by two strata (Carroll & others, 1993).

The results of numerous studies provide evidence that individual differences in psychometric scores stabilize at about age five or six (Z. Chen & Siegler, 2000). These scores are also good at predicting performance in school. More recent research has found correlations between the performance of infants in tasks such as visual recognition and intelligence quotient (IQ) scores later in life (Z. Chen & Siegler, 2000).

IQ tests throughout the last century show a sharp increase in IQ with every generation, to the point where someone who would have scored in the 90th percentile in 1892 would drop to the 5th percentile in 1992. These differences suggest that the environment in which children grow up plays a much more important role than genetics in determining IQ, since genetic mutations explaining these gains could not have occurred in such a short span of time (Sternberg & Kaufman, 1998).

Criticism of psychometric theories centers on the difficulty of capturing the richness of intellectual abilities through a few numbers. These theories have also been criticized for failing to take into account social and cultural issues, disregarding some of the factors that people from different cultures consider key to intelligence, and lacking a strong correlation with success in life (Z. Chen & Siegler, 2000; Sternberg & Kaufman, 1998). They also tend to be used as predictors of future performance, and not as a way to prescribe how to best educate children (Gardner & Moran, 2006).

Multiple intelligences

Gardner and Moran propose that multiple, somewhat independent, yet interacting intelligences provide a useful way for understanding human cognitive abilities (Gardner & Moran, 2006). They propose eight specific intelligences, each with a focus on different types of information: linguistic, logical-mathematical, musical, spatial, bodily kinesthetic, naturalistic (distinguishing between natural and manmade objects), interpersonal, and intrapersonal. Gardner argues that different combinations of intelligences are better matches for different types of professions. For example, he proposed that business people are better suited at having all intelligences at similar strength, while scientists and artists are better suited at having a few intelligences be particularly strong, overshadowing the rest (Gardner & Moran, 2006).

Gardner's ideas have inspired educators to make educational activities that teach concepts by introducing them through many entry points, taking advantage of children's multiple intelligences. Instead of concentrating only on linguistic or logical-mathematical intelligences, as a lot of educational activities do, Gardner's theory suggests involving additional types of intelligences to introduce concepts. The more entry points into a concept, the more likely a greater number of children will understand it. Kornhaber et al. discuss ways in which this approach has benefited students (Kornhaber et al., 2004).

Successful intelligence

Sternberg proposes the concept of successful intelligence as an individual's ability to succeed in life given the individual's goals within a sociocultural context (Sternberg, 2003). He argues that people achieve success by adapting to, shaping, and selecting environments. This process requires people to know about their strengths and weaknesses, and how to compensate for these weaknesses through analytical, creative, and practical abilities. These three abilities constitute the three interacting aspects of Sternberg's triarchic theory (Sternberg, 2003).

Sternberg and Kaufman argue that current educational practices overemphasize the use of analytical abilities to the detriment of creative and practical abilities. They propose that educational activities should match students' strengths in analytical, creative, or practical abilities (Sternberg & Kaufman, 1998).

Executive function

Executive function refers to a collection of processes necessary for goal-oriented behavior, which are crucial for children to succeed socially and academically. Increases in executive function skills have been associated with improvements in mathematical ability (Blair & Razza, 2007b; Bull & Scerif, 2001; Clark et al., 2010; Espy et al., 2004; McClelland et al., 2007), reading, emergent literacy and vocabulary (Blair & Razza, 2007a; McClelland et al., 2007), and theory of mind (S. M. Carlson & Moses, 2001). The advantage of focusing on executive function is that it can be improved independently of general intelligence (Bierman et al., 2008; Blair & Razza, 2007a). For this reason, executive function processes have been getting an increased amount of attention during the past decade.

A widely used instrument for measuring executive function is the *Behavior Rating Inventory of Executive Function* (BRIEF). In its second edition, BRIEF is organized across three regulation indices, each with multiple scales (Dodzik, 2017). These indices and scales provide a good sense of the types of skills encompassed by executive function and why they have such broad impacts on children's lives. The Behavior Regulation Index includes the Inhibit and Monitor scales, which measure children's ability to resist impulses, stop inappropriate behavior, and understand the impact of their behavior on others and on their goals. The Emotion Regulation Index comprises the Shift and Emotion Control scales, which relate to children's ability to switch attention appropriately and to regulate emotional responses to challenging situations. These scales are related to the concept of emotional intelligence (Mayer et al., 2007). The Cognitive Regulation Index is composed of the Initiate, Working Memory, Plan/Organize, Task-Monitor, and Organization of Materials scales, which are associated with the ability to accomplish goals by initiating action, holding and processing relevant information, generating plans, checking on progress, and being organized (Dodzik, 2017).

Significant challenges with executive function are associated with diagnoses for conditions such as Attention Deficit Hyperactivity Disorder, Learning Disabilities, and Autism Spectrum Disorder, among others (Dodzik, 2017).

When it comes to strategies for enhancing children's executive functions, there is evidence that aerobic exercise may improve cognitive flexibility and creativity, and martial arts may prove advantageous across a wide dimension of executive function skills (Diamond & Lee, 2011). Mindfulness training may also provide advantages, in particular when it comes to shifting attention and monitoring for events (Diamond & Lee, 2011). When it comes to curricula used in schools, two approaches stand out: *Tools of the Mind* (Bodrova & Leong, 2007) and Montessori (Montessori, 1964). Their common strategies used for enhancing executive skills include activities that connect children to each other and to the physical space around them, focus on oral language development, encourage self-talk, use scaffolds, emphasize planning by children, and promote character development, including kindness, helpfulness, and empathy (Diamond & Lee, 2011).

In spite of the increased attention being paid to executive function skills at individual schools, this is a topic that has largely escaped the attention of government officials, who are still largely focusing only on literacy and numeracy.

Summary

The field of child development studies how children change as they grow up. The ideas of Piaget and Vygotsky, which have been highly influential in the child-computer interaction field, form the basis of current research in child development as well. From Piaget comes the concept of adaptation, with children forming knowledge structures as they experience the world. Papert, a pioneer in designing computer technology for children, argues that the best kinds of experiences have children building public artifacts of their interests. Sociocultural approaches influenced by Vygotsky's ideas put a greater emphasis on the role of society, language, tools, and symbols in development.

More recent approaches to child development emphasize the notion of embodiment, with change occurring through interactions between the brain, the body, and the environment (including other people). They also incorporate the notion of plasticity, or how neural pathways can change. Plasticity tends to be greater at younger ages, meaning that experiences can have a greater impact on development earlier in life, and that there will be more within and between child variability earlier in life.

Interactive technologies can play a role in development by providing children with positive, richer experiences, thus setting a better environment for development. These experiences can involve using computers to motivate children, provide them with personalized experiences of interest they otherwise would not be able to access, and facilitate positive relationships with caregivers, teachers, and peers.

The child development literature can assist technology designers through insights on the typical abilities of children at particular ages and the types of experiences that are more likely to result in healthy changes. It can also provide ideas for the types of skills to develop (e.g., executive function skills) and various approaches that can inspire novel interactions with technology.

Chapter 3
Safety Considerations

Technologies do not always provide advantages to children and in fact may harm them. In the past, this has resulted in campaigns against the use of interactive technologies by children, or at the very least the use of computers in schools. While these campaigns tend to look only at the negative aspects of computers, they and others have pointed out risks in children's use of interactive technologies that must be taken into account. The following is a brief overview of these risks, together with suggestions on how to avoid them.

Physical considerations

Technologies for children need to follow common sense in their design to avoid physical injuries. The American Academy of Pediatrics provides such common-sense recommendations including avoiding sharp edges, toxic materials, and choking, squeezing or strangulation hazards (Glassy & Romano, 2003).

Technology and content designers should also be aware of less immediate physical impacts such as obesity. There is evidence that heavy television-watching leads to obesity, which increases the risk for type 2 diabetes and cardiovascular disease. The evidence increasingly points at exposure to advertisements for unhealthy food being the main culprit, as opposed to a sedentary lifestyle (Andreyeva et al., 2011; Association, 2000; Krebs et al., 2003; Pediatrics & others, 1986; Rideout, 2004; Zimmerman & Bell, 2010). At the same time, there is research suggesting that videogames can be used to lower obesity, given the right context (Calvert et al., 2013).

In terms of the challenges with advertising, computers have the potential of multiplying the current problem. Risden et al. (1998)

found that interactive advertising, where advertising is included as part of games, was more effective with 10-14-year-old children than advertising seen on television, with children more likely to recall brand names and products (Risden et al., 1998). Advertisers are certainly aware of this, as they have generated a new genre of games widely referred to as advergames, many of them targeted at children. In a more recent study, van Reijmersdal et al. found evidence that increased brand prominence in an advergame led to greater brand memory in 7-12-year-old children. At the same time, greater involvement with the game led to more positive associations with the featured brand. More worryingly, children's awareness of the advertising nature of the game had no impact on brand memory or positive associations with it (van Reijmersdal et al., 2012). A more recent development is the use of dark design patterns in apps targeting children (Fitton & Read, 2019).

Parents should make an effort to be aware of advertising content within games, and game designers should be upfront with parents on the advertisements placed within games. In addition, parents should be on the lookout for technologies that keep children from being physically active, as well as for the negative consequences of content that promotes unhealthy eating habits.

Intellectual considerations

Another area of inquiry that has some relevance to young children's use of computers is the research on the impact of viewing television. Obviously, most interactions with computers are likely to be more active than those with television, but some of the concerns raised by critics of young children's use of computers (Alliance for Childhood, 2001) are similar to those raised about television viewing. The results of studies suggest that the effect of television is highly dependent on the type of programs watched and how children watch them.

An example of this comes from a study by Linebarger and Walker (2005) who surveyed parents every three months about their children's television viewing from the time the children were 6 months old until the age of 30 months (Linebarger & Walker, 2005). After controlling for parental education, home environment, and the children's cognitive performance, they found, not surprisingly, that different programs had different impacts. The common characteristics of the shows that led to better results included child-directed speech, elicitation of responses, object labeling, and/or a coherent storybook-like framework.

A similar study by Schmidt et al. did not delve into actual shows, but followed children's television viewing habits at 6 months, 1 year, and 2 years of age, followed by an evaluation of language and visual motor skills at age 3 (Schmidt et al., 2009). They found that after adjusting for maternal age, income, education, picture vocabulary test, marital status, child's age, gender, birth weight, breastfeeding, race/ethnicity, primary language, and speech, that television viewing was not associated with differences in language or visual motor skills at age 3.

Another large study by Zimmerman et al. consisted of a single survey of 1,008 parents of children ages 2 to 24 months. They found that after adjusting for sex, age, number of siblings, premature birth, hours per week in daycare, parental presence, income, race/ethnicity, and state of birth, viewing of baby-oriented videos (e.g., Baby Einstein) was correlated with a significantly lower Communicative Development Inventory score for children ages 8 to 16 months. Other types of content did not have a significant impact. (Zimmerman et al., 2007)

To summarize, there is more information about the impact of television on infants and toddlers than about the impact of computers. In particular, the research literature points at a complex set of factors that influence whether television has a positive or negative impact. Of particular note is that certain types of shows are more likely to lead to cognitive gains. This nuanced view has now made its way to recommendations by the American Academy of Pediatrics ("Media and Young Minds," 2016), which used to take a stronger stand on young children and screen time based on earlier studies that did not take into account all the factors of the studies presented above (Christakis et al., 2004; Rideout et al., 2003).

In terms of specifically studying the impact of computers on young children's learning and cognition, a group from Wayne State University conducted the most thorough examinations thus far; however, these studies are dated at this point. They did so through studies with children enrolled in Head Start, a United States program that provides early childhood education, health, and nutrition to low-income children ages 3 to 5. Their correlational and controlled studies consistently found that computer use positively impacted school readiness (Fish et al., 2008; X. Li et al., 2006; X. Li & Atkins, 2004; McCarrick et al., 2007; McCarrick & Li, 2007). Plowman and Stephen studied the ways in which adults can actively support preschool children in their interactions with technology, which included demonstrating, explaining, instructing, monitoring, providing feedback, arranging for access to technology, setting up activities, and checking on levels of engagement (Plowman & Stephen, 2007).

Other researchers who conducted similar studies include Castles et al., who found a positive correlation between computer use and letter knowledge even after controlling for cognitive and environmental factors, based on a survey and testing of 1,539 4-year-old children (Castles et al., 2013).

Chapter 10 provides details on research on computer-based activities for learning, including computers in school programs, focusing mostly on older children.

Obviously, what matters most with children's media is not so much whether children access it or not, but what they access, how they access it, and for how long. The quality of media (e.g., violent, slapstick, or fun and educational), the amount of time children spend with it, and how they experience it (e.g., alone or with a parent providing guidance and feedback) are factors that will all have a significant impact on outcomes.

Social, emotional, and moral considerations

Television has also been linked to reduced time talking with friends and family as well as diminished time spent playing outdoors (Rideout et al., 2003). Furthermore, the media content children access can also affect emotional health by causing fear, depression, nightmares, and sleep problems (American Academy of Pediatrics, 2001). The most severe problems though have been linked to violent content. Viewing of television violence during childhood has been linked with violent and aggressive behavior during both childhood and adulthood in both males and females regardless of socioeconomic status, intellectual ability, and parenting factors such as aggression and television habits (Huesmann et al., 2003; L. A. Robertson et al., 2013).

A study that differentiated between types of children's television found that children ages 2 to 5 who watched violent television programs were more likely to have antisocial behaviors between the ages 7 and 10 than those who watched non-educational, nonviolent television, as well as educational nonviolent television programs, with the lowest associations with antisocial behavior for the latter (Christakis & Zimmerman, 2007).

Violent videogames have also been linked to aggression. Lieberman warns against the negative consequences of violence in media content experienced by children, which can lead to violent and hostile behavior, desensitization to the pain and suffering of those on the receiving end of violence, as well as fear and anxiety (Lieberman, 2001). Höysniemi and Hämäläinen provided an example of the effect of violent videogames when they found that a game in which players use real martial arts moves to fight virtual opponents led young children to misunderstand the consequences of violent behaviors, such as throwing punches and kicks. The authors provide the example of a 4-year-old who punched his father, but did not think the punch would hurt (Höysniemi & Hämäläinen, 2005). To avoid these issues, if violence is shown, it should be shown together with its negative consequences instead of being glorified, rewarded, or presented as entertaining (American Academy of Pediatrics, 2001).

On the other hand, a study by Ferguson of 302 teenagers found no relationship between violent television or videogame viewing and serious acts of aggression or violence. Ferguson did find that depression and antisocial traits were the strongest predictors of aggression and violence. He also found that children who played more violent videogames were more likely to bully other children (Ferguson, 2011). The differences in results may be due to different populations in the studies (the cohort in the Ferguson study is entirely from a small city), and different outcomes measures. For example, Ferguson measured serious aggression based on a questionnaire that measures psychopathology. However, smaller levels of aggression also matter and add up in a society, whether they involve bullying, caring less about how our actions impact others, or ignoring basic forms of politeness that help us function better together.

Hull et al. provided evidence of these smaller issues in a longitudinal study of teen use of mature-themed, risk-glorifying videogames. They found that teens who spent more time playing this genre of videogames as well as videogames that involved protagonists who represent non-normative and antisocial values were more likely to engage in alcohol use, cigarette smoking, aggression, delinquency, and risky sex (Hull et al., 2014).

Looking at the short-term impact of video games, Chang and Bushman asked pairs of 8- to 12-year-old children to play or watch video games with various levels of violence, followed by moving to a room where they could play with toys and games. The room included two disabled handguns. The children who played a violent video game were more likely to handle a handgun and pull the trigger more times, including in their own direction or in the direction of their play partner, than those who did not play a violent video game (J. H. Chang & Bushman, 2019).

Content may also have negative effects in terms of risky sexual behavior and drug use. Instead of showing these activities as being casual, fun, and exciting, content providers should either avoid showing them or show them together with their negative consequences (Bar-On et al., 2001; Strasburger et al., 2010). However, interactive violence and risky behavior have been around for decades in videogames. The difference with most recent offerings is that these interactive behaviors are much more realistic, while before they were represented with a few pixels. This makes the violence and risky behavior seem as lifelike as it may be on a television show, with the added first-person factor, as opposed to the child as a passive consumer. While rating systems, parental controls, and involved adults do help, there are still plenty of children playing this type of game without guidance and feedback.

Media content and videogames can also provide children with negative gender, ethnic, and racial stereotypes (Signorielli, 1998). For example, Burgess et al. found that problematic patterns in media content and videogames have yet to change. In one study looking at videogame magazines, they found that minority males were much more likely to be represented as athletes or in aggressive roles, and less likely to be shown in military gear or using technology than white males. In a second study on videogame covers, they found that minority males were more likely to be presented as aggressive “thugs” and athletes than white males were. Minority females were almost completely absent from video magazines and videogame covers (Burgess et al., 2011). There have been improvements though as a study of video games between 1983 and 2014 found an increase in female playable characters and a decrease in their sexualization (Lynch et al., 2016). However, female characters are still more likely to be in secondary roles and to be sexualized (Lynch et al., 2016).

Gender themes can be problematic too, as Joiner found that merely changing the motivating theme for a game to make it more stereotypically thematic for girls did not make it more attractive to girls, but made it less attractive to boys (R. W. Joiner, 1998).

Designers may have to go beyond motivating themes to engage children. For example, Passig and Levin found that the way of interacting with a multimedia application impacted kindergarten children's satisfaction differently depending on gender. Girls valued being able to write as they learned, receiving help, and the visual appearance of the application, while boys valued control, speed, and navigation (Passig & Levin, 2001). Later, Greenberg et al. surveyed fifth, eighth and eleventh grade children about their videogame use and preferences. They found that boys played, on average, at twice the rate girls did, and were more likely to prefer physical games that included sports, shooters, and racing. Girls, on the other hand, were more likely to prefer traditional games, such as classic arcade, quiz/trivia, card/dice, and board games (Greenberg et al., 2010). A more recent study found similar outcomes, with boys much more likely to prefer sports games and girls much more likely to prefer mini-games (Tatli, 2018). Similar results were found in adults (Phan et al., 2012).

Children can also be affected by content created or distributed by other children. This is often referred to as cyberbullying, where children use technology to harass, threaten, torment, humiliate, or embarrass other children. The technologies of choice vary, but these attacks can involve harassment through social media, text or instant messages, emails, postings on websites, impersonation, identity theft, malware, or embarrassing videos or pictures. Estimates of the prevalence of cyberbullying go as high as more than half of children affected at least once a year. The outcomes of cyberbullying are overwhelmingly negative, with reports of it leading to anxiety, depression, substance abuse, difficulty sleeping, lower academic performance, lower school attendance, and in a few cases murder or suicide. In a meta-analysis of cyberbullying studies, Kowalski et al. found that the best predictors for someone perpetrating cyberbullying were being a victim of cyberbullying, and participating in traditional bullying, with empathy and school environment (e.g., respect, fairness, and kindness of staff) being the best protectors for preventing bullying. The best predictors of being a victim of cyberbullying were being a victim of traditional bullying, and participating in traditional bullying, while the best protectors were school safety and environment (Kowalski et al., 2014). A follow-up review by the same lead author found similar results, with a worrying increased risk for girls to be cyberbullied, as well as a well-documented increased risk for children who spend more time online and children with low self-esteem (Kowalski et al., 2019). In addition, they identified some evidence of increased risk for children who do not identify as heterosexual or who have a disability or obesity (Kowalski et al., 2019). They found strong evidence for parental warmth and family support to be protective factors (Kowalski et al., 2019).

Another issue to consider is the long-term consequences of technology use on privacy. Children are growing up in a world where more and more of their lives are digitally recorded. These digital recordings of their lives include pictures and videos taken and shared by caregivers, school and medical records, the use of digital technologies, as well as information from surveillance technology (e.g., surveillance video) and apps designed to provide free services in exchange for personal information. This trend will almost surely continue. On the one hand, it may be interesting for someone to remember what they did on a particular day, or the way they went about creating something of which they are proud. In that sense, there are positives to having a digital history. The problems occur when people are not in control of their own information, especially information from their childhood. A possible solution is for technologies to ensure that people are able to manage information about them that was created when they were children, even if their parents gave permission for it to be used. This is a challenge for designers of all technology, not just technology for children. It is also a challenge that will at least partially involve legal issues.

In Chapter 8 the subsection on “Safety and privacy” provides examples of research on this topic, including educational and parental perspectives.

Summary

Like any other technology, the use of computers can have positive or negative impacts on children. What matters in determining the outcome is the type of technology used, the context in which it is used, and the frequency of use.

This chapter presented an overview of various risks that can occur when children use computer technology. Risks include physical (e.g., obesity), intellectual (e.g., language development), social (e.g., isolation), emotional (e.g., cyberbullying), and moral issues (e.g., gender stereotyping).

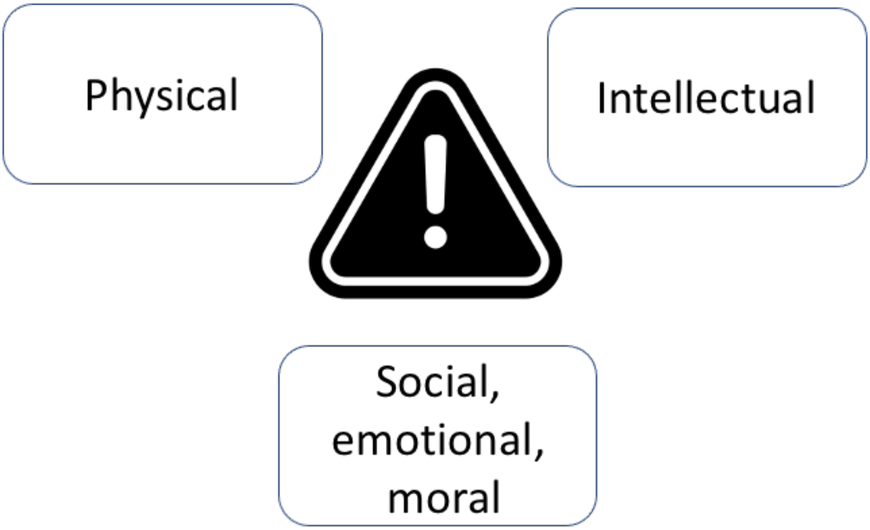

Figure 5. Potential risks associated with children's use of computers. Icon by Eko Purnomo from the Noun Project.

Technology designers should take these risks into account to make it less likely that technologies will have a harmful impact on children. Likewise, they can take a more active role in recommending frequency and context of use, for example, by making it easier for parents to participate in children's technology use, track the amount of time children spend on computer-related activities, and compare it with a healthy frequency of use.

Designers can also recommend healthier contexts of technology use that involve parents, caregivers, or other children in computer activities, and that place these activities in locations where responsible adults can easily participate even if it is for brief amounts of time (e.g., in a living room instead of the child's bedroom). Taking these steps should help reduce risk and make it more likely that children may benefit from interacting with computers.

Chapter 4
Usability and Children

A sensible goal when designing technologies for children is to make them "child friendly," but what exactly does this mean? Is it something measurable? Usability has long been a concern of fields such as human-computer interaction and the broader human factors community. The idea behind *usability* is simple: that people using any technology, from computers to hand tools, should be able to accomplish whatever they set out to do quickly and accurately. This concept of usability, developed for adult users of technology, assumes that people are using technology to complete specific tasks. It has worked very well for the application areas that were the early focus of human factors research and practice: business, industry, science, and the military.

For children, however, the goals are often different. From a societal perspective, the goals for technology design are more likely to focus on positive development across physical, social, intellectual, and emotional dimensions. These goals may mean that not everything should be easy to do, but that there should be appropriate challenges in order for children to learn. From a personal perspective, children are more likely than adults to value the quality of the experience they have using a technology. There are likely to be situations when children want to accomplish tasks quickly and accurately, but this will usually happen within the context of an experience they want to pursue.

One aspect in which traditional concepts of usability and user experience often fall short is in addressing the needs of people with disabilities, including children. When user experience and usability are considered, they should be considered for a wide range of abilities.

No matter the population, something to consider when thinking about usability and user experience is that different children, contexts, tasks, and technologies will determine different levels of importance for each usability and user experience goal. For example, entertainment may be more important for some types of technology and learning more important in others. Design teams should determine which goals are most important in a given project in order to better guide the development and evaluation of technologies.

This chapter discusses the concepts of usability and user experience with a focus on how they apply to children. The remainder of the chapter includes discussions of user experience and usability goals. Chapter 5 discusses principles and heuristics that can help improve usability, while Chapter 6 discusses design and evaluation methods, including how to measure usability and user experience.

User experience

User experience refers to how it feels to use a technology. But what are the feelings that matter? This section explores experience and feelings from the perspective of Csikszentmihalyi's optimal experience. It also briefly discusses other user experience concepts typically used by usability professionals with adult users.

Optimal experience

When studying what makes people happy, Mihaly Csikszentmihalyi, a well-known research psychologist, came across specific components of what he referred to as *optimal experiences* (Csikszentmihalyi, 1990). The components he identified can be useful when thinking about designing technology-based experiences for children because experience is so important to engaging and motivating children, and because the components he identified have direct links to learning.

Having a *challenging activity that requires skill* is one of the components observed by Csikszentmihalyi. This component ties directly to children's motivation to learn, but also poses a challenge to designers. For an activity to have the right level of difficulty, it needs to strike a balance. If it is too challenging, children may become anxious or frustrated. On the other hand, if the activity is too easy, children may find it boring. Recent video games take this into account by adjusting the difficulty of the game automatically based on the gamer's performance. Likewise, technologies for children should enable them to advance to more challenging possibilities as they improve their skills.

Another way to increase challenges is to add *novelty* to experiences. For children, novelty is necessary in order to have rich experiences that can lead to growth. At the same time, it needs to occur in such a way that it does not overwhelm them and cause anxiety. Through novelty, and the right amount of challenge, children may learn optimally. In fact, Csikszentmihalyi observed that people were more skilled after going through an optimal experience (Csikszentmihalyi, 1990). This is one reason why technologies for children should be designed in such a way that they enable children to become more skilled over time, with these greater skills leading to greater accomplishments.

Csikszentmihalyi also emphasizes having a *sense of control*, which is directly related to avoiding anxiety. According to him, when participating in optimal experiences, people are able to exercise control even in difficult situations (Csikszentmihalyi, 1990). But again, there needs to be a minimum level of challenge in order to avoid boredom.

Another component of optimal experiences is the *merging of action and awareness*. This involves having all attention focused on the activity, resulting in a loss of self-awareness, and a feeling of being one with the activity (Csikszentmihalyi, 1990). These are largely indicators of a high level of engagement and immersion with an activity. In particular, the feeling of being one with the activity is likely to require technological interactions designed in such a way that they feel natural and provide a sense of control.

Csikszentmihalyi also observed the need for having *clear goals and feedback*. In order for the experience to be optimal, people need to know whether they are making progress (Csikszentmihalyi, 1990). The use of the appropriate amount of feedback timed correctly has long been discussed in the human-computer interaction literature. In this case, no matter what activity children are doing, whether it is telling stories, building, solving a puzzle, or performing music, it is clear that they need appropriate feedback in order to learn optimally.

Csikszentmihalyi also observed that when people participate in optimal experiences, they experience a *transformation of time*, which seems to go much faster (Csikszentmihalyi, 1990). This feeling should be familiar to anyone who ever experienced an optimal experience (e.g., chatting with a dear friend, playing a video game) and did not realize how much time had gone by. This concept has been used in usability testing, with asking participants how long they think a particular task took and comparing their answer to the actual amount of time. While young children may have difficulty estimating time, it can still be a useful measure if the target audience is older children.

More recent research by O'Keefe and Linnenbrink-Garcia found that there are two additional components that matter to entering an optimal experience. The first is *emotional interest,* meaning how people feel about participating in an activity. The second is *personal significance*, or how important the activity is to the person participating in it. In the studies conducted by O'Keefe and Linnenbrink-Garcia, participants who had high emotional interest in an activity of high personal significance performed better than those who did not (O'Keefe & Linnenbrink-Garcia, 2014). Their research suggests that interaction designers need to find ways for children to connect emotionally with technologies in activities that matter to them, in order to engage these children in optimal experiences.

Other kinds of user experience

To evaluate user experience for adults, usability professionals use questionnaires that ask about feelings that are associated with positive user experiences. These include whether the experience was enjoyable, fun, entertaining, helpful, motivating, or rewarding. Most, if not all, of these feelings are likely to be elicited through the optimal experiences discussed in the previous section. It is also important to remember the social aspects that are often important in positive experiences. Therefore, having a user experience that strengthens friendship, or helps establish a connection with a loved one can also be considered a goal.

Usability goals

While it is important for children to encounter challenges when using technologies in order to have optimal experiences, these challenges need to be in the right places. For example, if children are using a visual programming environment, the challenges should be in devising algorithms, not in manipulating the program. Designers need to make sure that user interfaces will not get in the way of children learning and using their skills to master challenges that matter.

In that sense, usability goals that are regularly used in usability studies with adults, such as efficiency and effectiveness, also apply to children’s low-level interactions with technologies. For example, children should be able to quickly and accurately move instructions when using a programming environment.

These usability goals can be used to compare different versions of a technology, or two technologies that can be used to accomplish similar tasks. Usability professionals typically measure usability goals through usability testing, which involves children completing specific tasks while their behavior is recorded and measured. Usability testing can also be used to uncover problems that prevent children from completing tasks when using a technology. Below are the most commonly cited usability goals (Preece et al., 2015).

Efficiency

In the field of usability and user experience, *efficiency* is usually measured based on the time it takes to complete specific tasks using a technology. Alternatives include counting the number of steps it takes to complete a task (especially if all steps are of similar difficulty), or using some form of user modeling, such as the keystroke-level model (Card et al., 1980), or more sophisticated forms of user modeling.

While time to complete tasks may be a useful measure for older children who need to accomplish tasks under time constraints, it is less likely to be a concern when designing for younger children. In addition, it is much more difficult to measure time spent on a task for younger children, as they may be more easily distracted while conducting tasks, and may not necessarily try to complete them as quickly as possible. On the other hand, excessively long times to complete simple tasks should be of concern at any age.

Steps to complete a task may be more consequential than time, and could prove a more useful measure of efficiency for children. Fewer steps are likely to indicate a simpler user interface that may enable children to more easily engage in activities.

Effectiveness

Effectiveness in user experience refers to how accurately and completely users can complete tasks using a technology. This is usually more important than efficiency for technologies designed for children, with lack of accuracy often being the cause of lower efficiency. For example, targets such as icons should not be too small to point at with a mouse or finger.

In terms of completeness, in some cases, it may also be appropriate to provide children with support to guide them through the steps required to complete a task. This approach can help ensure that they do not skip steps or think that they have completed a task when there are still remaining steps.

Learnability

The younger the children, the less likely they are to want to spend time learning how to use a technology. In recent years, technology for children comes with a minimum set of instructions, often delivered on the device (or screen) itself. There is usually no need for reading a manual, or for instruction in the classroom. Older children may use more complex technology that could require instruction, but generally the expectation is that children should be able to explore a technology without having to go through training beforehand.

The goal of children being able to start exploring a technology with minimal instruction does not mean that there is no learning as they use it. In fact, the concept of *multilayer user interfaces* could be used to start out with a simple user interface that increases in complexity as children explore more options (Shneiderman, 2002). Adjusting the level of challenge and complexity based on individual children's current expertise can lead to optimal experiences.

Memorability

In usability and user experience, *memorability* refers to the ease of recollection of how to use a particular technology. Typical ways of testing for memorability with adults involve teaching users how to use a technology, and bringing them back days, weeks, or months later to see what aspects they recall.

It is difficult to think of situations in which it makes sense to test for memorability in children's technologies. For adults, testing for memorability makes sense for technologies that they are likely to use infrequently and that involve some amount of learning, such as software to file annual tax returns. While there may be similar situations for teenagers (e.g., software to sign up for courses), it is less likely to matter for younger children as technologies designed for them should be easier to learn, and more likely to be used frequently.

Utility

Utility refers to what can be accomplished with the technology in the context of user experience. Companies often use comparison charts showing how their product has more features than those of competitors, or how more expensive versions of the same technology have more capabilities. For young children though, fewer functions may lead to better results. Simpler user interfaces where only a few operations are possible (but that still provide a wide range of possible outcomes) are better suited for children than user interfaces with a greater number of operations. For example, a touchscreen drawing program that enables children to draw with a stylus and pan and zoom with their fingers has very few operations but provides a wide range of expressive possibilities.

It is also possible to use a multilayer approach, as described in the subsection on learnability, increasing the number of options and the functionality available as children progress in using the technology and are ready for new challenges. Many videogames use the multilayer approach, where gamers can be successful using simple commands at first, but as the difficulty level increases, have to learn more complex commands.

Summary

Usability has been widely explored in the human-computer interaction and human factors communities, but for the most part only as it relates to adults without disabilities, with goals that fit business, industry, military, and scientific applications. A challenge when thinking about usability for children is to examine what it means for a technology to be usable by children: what goals are most important? It is also important to remember the needs of children with disabilities.

Key usability goals will vary based on the technology itself, the user population (i.e., who is going to use the technology), and the context of use. At a high level, technology designers should consider user experience goals: how should it feel to use the technology? Csikszentmihalyi's concept of optimal experience can be useful in helping identify enjoyable experiences for children that can lead to optimal learning opportunities. At a lower level, more traditional usability goals, such as efficiency, effectiveness, and learnability, can be used to ensure that children are able to learn basic interactions and complete them in a reasonable amount of time with high accuracy.

Chapter 5
Design Guidelines

As interaction designers have gained experience developing and critically analyzing technologies for adults and children, they have also constructed design guidelines. The original sets of guidelines come from the human-computer interaction community at large, while the child-computer interaction community has added additional guidelines, mainly through empirical studies.

These guidelines tend to be quite general. Not all of them apply to every project and every circumstance. However, they are useful rules of thumb to keep in mind when developing and improving designs.

This chapter focuses on a discussion of the classic guidelines from human-computer interaction within the context of designing for children. More specific guidelines for visual design, use of audio, and the use of specific interaction techniques can be found in Appendix B.

Revisiting guidelines for adults

Some of the most influential human-computer interaction guidelines come from Don Norman's bestseller *The Psychology of Everyday Things* (first released in 1988, later re-released as *The Design of Everyday Things*) (Norman, 1988), Ben Shneiderman's golden rules (Shneiderman et al., 2016), and Jakob Nielsen's heuristics (J. Nielsen, 1994). While these pioneers in the field of human-computer interaction did not necessarily develop them with children in mind, they are generic enough to be applicable to children.

In this section, the guidelines are organized across three dimensions that are interrelated: perceivability, operability, and developmental fit. At a high level, they respectively concern how well children can perceive and operate a user interface, and whether the interface is developmentally appropriate. Each of the guidelines may differently affect children with disabilities, such as children with vision, motor, hearing, or cognitive impairments.

Perceivability

The concept of *perceivability* is directly tied to Norman's concept of *visibility*, but clarifies that user interfaces are not solely visual. A user interface that is easy to perceive should make clear to children what they can do with the technology, and what the technology is currently doing.

Accomplishing this goal for children may be more challenging than it is to do for adults. For example, user interfaces with a large number of visual options and status updates may be appropriate for adults, but would likely be challenging for young children due to limited information processing, attention, and working memory abilities. The concept of *simplicity* is important to consider, therefore, when designing for children. The challenge is how to provide powerful technologies that do not involve complex user interfaces. Designers should strive to limit the number of user interface components in order to increase perceivability.

Another concept that is often cited for adults is *speaking the user's language*. In the case of children, the most appropriate language will often not be written language, but images or sound. An obvious challenge in this area is addressing the international use of a technology. For example, children in the United States tend to use erasers on the back of their pencils, while children in other regions of the world use larger erasers that they grasp with their hands. These regional differences can lead to different visual representations for tools in a user interface. Therefore, even visual designs related to simple concepts such as erasing should consider the international dimensions of use.

Related to *speaking the user's language* is the concept of *mappings*, one of the many cited by Norman in *The Psychology of Everyday Things* (Norman, 1988). When it comes to perceivability, it is important to consider the mapping between what children want to accomplish and what appears available in the user interface. The concept of mappings captures that not only is it necessary that children understand what options are available, but that these options match what children may be interested in doing with the technology. This may differ a bit from the traditional concept of mappings, which assumes that an adult knows what they want to do, and wants to do it as quickly and accurately as possible. As discussed in the previous chapter, children may have other goals, such as entertainment, exploration, and learning. A natural mapping then may not necessarily correspond to something specific that children want to accomplish, but may instead be fulfilled by providing children with options that are compatible with their high-level goals.

One last concept related to perceivability is often referred to as *recognition over recall*, meaning that people can more easily recognize than remember something. For example, most people will have an easier time recognizing the names of their first-grade classmates than recalling the same names. In user interfaces, this guideline drove the shift from command-line user interfaces that required users to memorize commands and their syntax, to graphical user interfaces that only require users to recognize options. This guideline does not mean that children are not capable of using command-line user interfaces, as in the 1980s when many children learned to program using *Logo* or the original *Basic* programming language, both of which required learning a relatively small set of commands and syntax. However, there is no doubt that the move to user interfaces based on recognition has made technology more accessible to a greater number of children, with the descendants of *Logo* (e.g., *Scratch*) moving to a recognition-based approach (see *Programming* section in Chapter 7).

Operability

The concept of *operability* is relatively simple: can children operate a specific technology? This involves some obvious guidelines, such as ensuring that children can physically reach a user interface, that physical controls are not too difficult to operate (e.g., buttons too hard to press), and that visual targets are large enough for children to select accurately. The main complication with these simple guidelines is that the needs are likely to be different for each age group. Designers should understand how young their users are likely to be and ensure that the youngest users are able to operate the user interface without difficulty.

Being able to operate a user interface is also related to knowing how to operate it. The concept of *affordances*, which Norman borrowed from James J. Gibson's ecological psychology (Gibson, 2014) is useful to address this challenge (Norman, 1988). It refers to the perceived or actual properties of an object given the child's abilities, goals, plans, and so forth. For example, a physical button should have visual attributes that make it obvious that it can be pressed. Interactive visual elements should be clearly distinguishable from non-interactive elements, and it should be obvious how to interact with them (e.g., selecting, swiping, sliding).

The use of *constraints* can also be beneficial to enable easier operation of technology. Constraints ensure only reasonable outcomes are possible when using a technology. For instance, elevators provide a simple example of constraints. Instead of instructing an elevator to go up or down a certain number of centimeters, the elevator provides a handy shortcut of buttons to go to specific floors. Likewise, constraints can be important in technologies designed for children to avoid undesirable outcomes.

Developmental fit

Developmental fit refers to children's ability to understand how to use a technology in a positive, constructive way. This ability will depend on children's prior experiences with technology, as well as with their cognitive abilities (e.g., memory, learning, attention), and the social and physical context in which they use technology. A technology with a good developmental fit will be developmentally appropriate.

One way to design user interfaces to make them more accessible is to break up complex tasks into simpler ones. If this approach is combined with Shneiderman's recommendation (Shneiderman et al., 2016) of *rapid, reversible, incremental actions*, then the user interface will be more likely to invite children's exploration. Even if they select an option that does not lead to a desired outcome, they can easily undo their action and select a different option.

In order for rapid, reversible, incremental actions to work well, they need to go hand-in-hand with an appropriate amount of *feedback* to help children understand what the technology is doing. Most importantly, children should be able to clearly perceive the consequences of their interactions with technology as quickly as possible. The subsection on direct manipulation in Appendix B discusses this topic in greater detail.

Another guideline that can help make user interfaces easier to master is *consistency*. This applies to following style guides to standardize the look and feel of technologies. It also means that performing the same operation on different objects or screens should have the same effect.

Something additional that can be added as a good complement to the other guidelines is to strive for *error-free technologies*, or technologies where children cannot reach error states, but instead may end up exploring something that they were not interested in exploring. Designing technologies where errors are nonexistent can reduce frustration and encourage children to fully explore technologies.

Adding *personalization capabilities* to technologies can also help make them more appropriate for individual children. This approach may involve adjusting the complexity of the user interface and the challenges it presents to individual children or may even present different interactive content based on children's interests and needs. Aesthetics can also be customized to address individual preferences.

Supporting *social use* can also be important for children. Considering embodied and sociocultural views on development, the ability to involve others in learning is very important. For this reason, technologies should be designed to favor social use with peers, caregivers, and teachers. Technologies do not need to be designed to be constantly used together with others, but they should make it easy for children to incorporate others in their activities. This goal could be accomplished by making it easy for individuals to work together, or at the very least enabling easy sharing of items created using a technology.

An even higher-level concept to consider is designing the *ecology of use*. The idea is to design technologies while taking into account their full context of use, including physical and social contexts. In some cases, it may be useful not to stop at designing a technology, but to also develop activities to conduct with the technology, or set up physical environments. At the very least, designing for the most likely contexts of use is necessary (Gelderblom & Kotzé, 2009).

Summary

Design guidelines provide high-level advice and were originally developed for adult users. However, they also largely apply to children's user interfaces, with some special considerations. While they do not apply to every project and every circumstance, design guidelines are useful in helping steer designs and addressing questions of perceivability, operability, and developmental fit. The guidelines involve concepts such as simplicity, mappings, recognition over recall, speaking the user's language, affordances, constraints, feedback, consistency, personalization, social use, and the ecology of use.

Chapter 6
Design and Evaluation Methods

With editorial feedback from Mona Leigh Guha, University of Maryland

A contemporary technology design project typically involves a design team working on the project over the course of weeks, months, or years. These projects can be quite complex in terms of technology, and may involve large design teams. Design teams use design and evaluation methods as guides in technology development projects. These can involve methods that outline overall strategies and philosophies to be pursued, as well as low-level activities that may be conducted on a specific day. This chapter covers the most commonly used design and evaluation methods, and includes recent research developments.

When undertaking the design of an interactive technology for children, it is important that design teams carefully consider which methods are likely to work best based on available resources, the characteristics of the child population, the type of technology being designed, the experience of the design team, time constraints, and so forth. Likewise, once a method has been selected, there may be many types of activities that can be conducted within that method. These again should be selected based on the various needs and constraints of a given project at a given time.

The first section of the chapter provides an overview of lifecycle models, the processes developed primarily by software engineers to better organize software development. Lifecycle models provide methodologies that can guide design teams with overall strategies and philosophies. This is followed by a discussion of the various roles children can play during software development, which often need to be decided before embarking on the design of a new technology. The last section of the chapter delves into specific design and evaluation methods and activities, including those used to obtain requirements, develop design ideas, and evaluate designs. It provides a detailed view of the options design teams have as they go through the steps necessary to develop a technology.

Lifecycle models

Lifecycle models outline the phases and strategies involved in designing and developing technology. These phases typically include identifying needs and establishing requirements, designing the technology, implementing versions of the technology, and evaluating requirements, designs, or prototypes. While versions of lifecycle models began to be described as early as the 1950s (Panel, 1956), they did not begin to be used widely until the 1970s (T. E. Bell & Thayer, 1976). The field of software engineering has worked on improving lifecycle models with the goal of efficiently managing resources and producing better quality technology.

Early versions of lifecycle models tended to follow a linear approach, with one phase of development followed by another, which caused serious problems when there were mistakes in the early phases (e.g., missing requirements). For the past 30 years, research on lifecycle models has had an emphasis on iterative approaches, where the requirements, design, implementation, and evaluation phases are repeated, usually adding depth and complexity during each iteration. Modern approaches also tend to emphasize speed in iteration, expect changes in requirements or designs to occur, and stress the need to engage with stakeholders, as well as close (face-to-face if possible) collaboration between all team members. An example of one of these models that is widely used is agile software development (Cockburn, 2006).

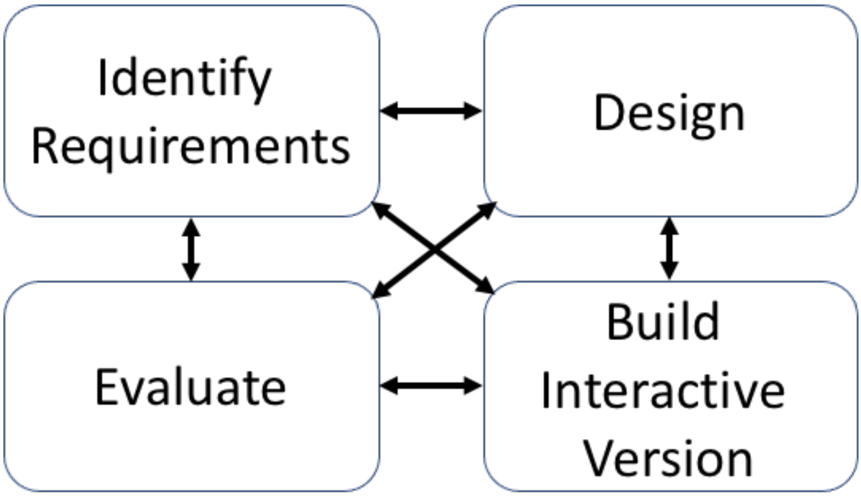

Figure 6. Modern lifecycle models provide for quick iterations between phases to identify requirements, design, build interactive versions, and evaluate.

The human-computer interaction field has contributed to these methods by proposing a greater emphasis on the involvement of users. In particular there is an expectation of user feedback during each design iteration. User-centered approaches usually go further with focusing on involving users and other stakeholders from the very beginning of projects, taking into account their opinions and feedback during all phases, and their performance when evaluating prototypes (Abras et al., 2004). Participatory and co-design approaches go further, seeking to directly involve users, in our case children, in co-developing design ideas (Muller & Druin, 2012). The ubiquity of technology has prompted calls for additional attention paid to the physical and social context of use.

Children's roles

Researchers and practitioners developed user-centered approaches with the primary idea of adults as users of technology. User-centeredness is often more challenging when thinking about children, especially at young ages. How well can they express their opinions? How much can we trust that their performance during testing represents typical behavior? Can they develop design ideas?

Since the mid 1990s, there has been a steady amount of research with the aim of answering these questions. Researchers have successfully developed and implemented methods and activities to involve children in the design process, from identifying requirements to evaluating technologies. The level of children's involvement in specific projects tends to vary based on practical concerns, such as budget and time constraints. Children's involvement also depends on the degree to which the leaders of design teams feel comfortable integrating them into the design process. There can also be challenges if children have diverse perceptual or cognitive abilities (Allsop et al., 2010). For example, children may have challenges in communicating and maintaining participation. Regardless of how involved they are, it is important to consider ethical issues whenever children participate in research or contribute to the design of technology, ensuring they are aware of how their actions and opinions will be used and that they make a well-informed decision to participate (J. C. Read et al., 2014). Likewise, children's participation should ideally involve activities for which there is evidence of intrinsic benefits to children (e.g., (Superti Pantoja et al., 2020)) or include evaluations of possible benefits (e.g., (Coenraad et al., 2019)).

To better discuss children's involvement in the design process, Druin proposed a classification of their involvement as users, testers, informants, or partners (Druin, 2002a).

Users

Montessori affirmed the need to observe children to learn what they need and what prevents them from learning (Montessori, 1964). Vygotsky highlighted the same need for observation in order to discover when children need help to acquire a skill or concept. Technology developers can also learn by observing children. Children can participate in the design process as users by being observed or by taking tests before and after using an already-developed technology (e.g., children being tested in math concepts before and after using a math learning app) (Vygotsky, 1978).

Children can participate as users at the beginning and end of the design process. Observing them at the beginning of the design process can provide key information for task analysis. Members of the design team can observe children's activities to learn about the situations in which technologies could aid children and to better understand their needs, abilities, and preferences. Members of the design team can also observe children using technologies that are competing or similar to the technology being developed. These observations can yield information on the features that work well, those that do not, and those that need to be added.

If the goal behind designing a technology is to help children better develop skills or competencies, then the design team may conduct research that involves testing children on those skills before and after using a technology, at the end of the design process. Such testing may require more planning and permissions than observing children, but often these tests are readily available (e.g., standardized tests). Testing for long-term effects, on the other hand, can prove logistically challenging. In addition to testing, the design team can also observe children while using the newly developed technology to learn about its positive and negative aspects.

Observation is a very practical and easy way of having children participate in the design process. At the same time, having children participate only as users greatly limits their role. With this type of participation, children do not affect the design of technology during the design process. The lack of direct design input from children has the potential to lead to the development of unappealing technologies that are difficult to use.

Testers

Perhaps the most common role children play in the design process is as testers. Intuitively, if a design team is designing for children, then at the very least it should test the technology with a group of children before releasing it to the public. While testing technology often brings up the idea of testing a fully developed technology, this need not be the case. Children can test low-fidelity prototypes (e.g., paper sketches), high-fidelity prototypes (e.g., interactive, but not fully functioning), and fully functional technologies at each design iteration. Testing greatly broadens the impact children can have on the development process.

The value of testing increases if the design team decides to use iterative design methods. By testing paper sketches, interactive wireframes, or other quick-to-build prototypes, designers and developers can eliminate many design bugs before implementing any of the technology. Removing design mistakes early in the process can be a valuable time and money saver. When testing early ideas and paper prototypes, designers should be careful to stay away from abstract ideas and present concrete concepts instead. Otherwise, children's developmental stages could interfere with their comprehension, unless the target population is older children or teenagers.

A useful technique that can bridge the gap between low-tech prototypes and implemented technologies is known as Wizard of Oz. In this technique, also used with adults, a human is controlling responses to input while the child thinks she is interacting directly with the technology. Wizard of Oz techniques are particularly useful for designing tangible, embodied, or natural language interactions. Höysniemi et al. provide a literature review of the use of Wizard of Oz techniques together with a useful example applied to a learning technology for children (Höysniemi et al., 2004).

Testing in the later stages of development is perhaps the most common way in which children currently participate in the design process. This kind of testing is crucial for ensuring that no major issues exist with the technology before it is released. Performing this kind of late stage testing alone is not recommended, however, because it may be too costly to fix basic design problems that could have easily been uncovered with earlier testing.

The process of testing technologies for children is not as simple as testing them for adult users for a variety of reasons. First, it is usually more difficult to recruit children to test technologies than it is to recruit adults. Furthermore, parents should be asked for permission to have their children participate in testing. Children should never be forced to participate, even if their parents give permission, and should understand they have the choice to stop participating in a test if they wish to do so. Adults conducting the testing should pay extra attention to ensure that the children feel comfortable as they test the technology. If those conducting tests observe signs of discomfort, they should ask the children to stop interacting with the technology. This is particularly important with younger children because they may not always voice their discomfort in front of an authority figure. For more detailed guidelines on testing with children, refer to Hanna et al. or Markopoulos et al. (Hanna et al., 1997; Markopoulos et al., 2008).

Testing throughout the design process can go a long way toward avoiding poor designs. However, it does not provide children with a chance to give their ideas to the design team, so the design ideas still come from adults.

For projects to succeed when children participate as testers and users, the design team should have a lot of expertise in the design of children's technologies and the design ideas must be based on sound educational or developmental theories (Cassell & Ryokai, 2001; Wyeth & Purchase, 2003). One way to keep children's developmental levels in mind is to use Bekker and Antle's developmentally situated design (DSD) cards. These are cards (similar in size to playing cards) that can be used by technology designers to quickly obtain age specific information about child development. During an evaluation with design students, the researchers found that the cards enabled the students to frame, orient, inspire, inform, integrate, and constrain their designs (T.

Bekker & Antle, 2011).

Informants

Another role children can play in the design process is that of informants, in which they share ideas and opinions with the design team and act as consultants, making their contributions at key points of the design process, the timing of which is decided by the design team. Scaife et al. developed the idea of children participating as informants in the design process, situating children's participation between that in user-centered and participatory design. They presented a framework that included iterative design that went from defining the domain and problems, to developing specifications, designing and testing low-fidelity prototypes, and later high-fidelity prototypes (Scaife et al., 1997).

Working with children while identifying needs and requirements can provide further information on the challenges and expectations involved in supporting their participation in specific activities. Children can also provide feedback and ideas by trying out existing technologies. As prototypes and design ideas are developed, children can provide feedback when the design team has a number of ideas or questions on how to move forward. Personal interviews, written questionnaires, or focus groups can provide children an opportunity to voice their opinions (J. C. Read et al., 2004).

For teams designing on the run, which often occurs in industry, having children participate as informants may be a convenient choice. If design teams are working 60-hour weeks dedicated to one project with a quickly approaching deadline, it is difficult for children to participate in the design process as equal partners; children are unlikely to have that sort of availability. Instead, it is more efficient and convenient for children to participate as informants providing feedback, opinions, and ideas at critical points (Brederode et al., 2005).

Design Partners

When children participate in the design process as design partners, they become part of the design team. They act as equal partners in the decisions leading to the design and implementation of technology. In this partnership, ideas come from a process of collaboration between adults and children. Children do not tell adults what to do, but do play a significant role in shaping the outcome of the process. More importantly, if the process works well, it is very difficult to trace ideas to specific partners, as they arise from collaborative activities between children and adults. Yip et al. studied co-design between adults and children and propose that design teams aim for balanced partnerships across the dimensions of facilitation, relationship building, design-by-doing, and elaboration (J. C. Yip et al., 2017). Such balanced partnerships can be achieved if children and adults facilitate sessions together, remain socially close, develop designs together, and integrate ideas together (J. C. Yip et al., 2017).

Druin pioneered the concept of children as design partners by creating design team partnerships with elementary school children at the University of New Mexico in the mid 1990s, and since 1998 at the University of Maryland (Druin, 1999, 2002a). Her approach has been replicated more recently by Jason Yip at the University of Washington (J. C. Yip et al., 2016). These teams follow Druin's Cooperative Inquiry method, which includes activities such as technology immersion, contextual inquiry, and participatory design (Guha et al., 2013).

Druin's approach is to set up a group of six to eight children to work on a set of projects. Her team recruits children through word-of-mouth, and the parents make a commitment to have their children participate in the design team for one year. Children in the teams need not be particularly smart or technology-savvy, just willing to share their opinions and listen to others. Note that adults in the team typically include child-computer interaction experts, engineers, computer scientists, designers, and educators. For specific projects, domain experts are often included in the team (e.g., librarians if designing a digital library) (see (Pazmino et al., 2015) for an example of involving domain experts), as well as adults who have built rapport with children, in particular when working with vulnerable children.

Druin's teams first meet for an intensive two-week camp during the summer when children are introduced to each other, to the adults they will be working with, and to the idea of being designers and inventors. Teams then meet twice a week during the school year, in meetings referred to as design sessions. Rather than working on one project, Druin's teams typically work on several projects at a time, although they usually work on only one project during a particular design session.

Many variables must be considered when selecting appropriate activities to conduct with design partners during design sessions. Walsh et al. presented a framework for the analysis and creation of these activities (Walsh et al., 2013). The framework is intended to help design teams select the best available activity by considering the people (including children) available to participate in the activity, the goal the design team wants to accomplish, and the characteristics of the activity itself. With regards to people, the framework considered the dimensions of experience in the design process (i.e., are the children and the rest of the design team familiar and comfortable with design methods) and the need for accommodation. With regards to goals, the dimensions were design space (i.e., what is being designed) and maturity of design (i.e., how far along is the project). While with regards to activity, the dimensions included cost, portability, technology, and physical interaction.

Having children join teams as design partners gives them a greater voice in the design process than they have in the tester or informant roles. Their needs and abilities can be more easily taken into account. In addition, adults can learn more about cultural differences between the generations. Design decisions will most likely include input from children, helping avoid designs that could be difficult to understand or uninteresting for other children.

There can also be partnerships with children who are experts in a particular topic. Yip et al. studied the difference between subject and design expertise when partnering with children in the design of technologies. They defined children with subject expertise as those who knew about the subject matter related to the technology being designed. Children with design expertise, on the other hand, knew more about usability or design aesthetics due to their experience in design team activities. The researchers conducted a study comparing how these two groups of children differed in their participation in design activities over three sessions. Examples of differences included the subject matter experts showing awareness of environmental constraints and practical matters, while design experts tended to be more exploratory and open in their design ideas (J. Yip et al., 2013).

Guha et al. provide a reflection on almost 15 years of experiences partnering with children at the University of Maryland. Changes over the years include accommodating different age groups than the original seven- to eleven-year-olds (e.g., adjusting methods to work with children in kindergarten). Challenges cited by the authors included partnering with remotely located children, and addressing mobile technology, social media, and search technology design (Guha et al., 2013).

Another challenge in including children as design partners is time needed to develop a multi-generational design team. Most children do not become inventors and designers overnight. They need time to develop the self-confidence necessary to tell adult researchers that their ideas will not work. It also takes time for children to realize that their ideas can actually be included in real products. In addition, it may take time for some children to fully understand what they are supposed to do in specific activities (C. Jones et al., 2003). In most cases, children do not make valuable contributions on a regular basis until they have been part of a design team for several months (Guha et al., 2013).

A useful rule of thumb then, is to have at least half of the children return to their design team every year. This leads to the issue of continuity. Not only is it recommended that some children return every year, it is also important for the team to meet on a regular basis throughout the school year. Putting together a team that works for a month, then does not meet for six months, will not likely help children develop into valuable contributors. These requirements can make design partnerships with children very difficult to implement for teams that have tight deadlines or short-term projects.

The logistics of setting up a design partnership with children can also be challenging. Not all researchers and designers have the ability to meet with children on a regular basis in a suitable space. It is also difficult to recruit children whose parents can reliably bring them to design team meetings. The children and adult researchers should also be able to work together. Social interdependence theory approaches can be used to address the challenge of collaborating effectively (Van Mechelen et al., 2015).

An additional challenge with multi-generational design teams and participatory design teams in general is that due to their small size, they are not representative of the entire target population. Hence, the children in the team are likely to bias the design toward their personal needs and abilities, cultural backgrounds, socioeconomic status, and likes and dislikes. A strategy to address this issue is to work with a second, larger and more representative group of children as informants. They can validate the work of the smaller group at key points in the design process (Druin et al., 2001).

A final challenge with this approach is that it often involves bringing the children to the design team instead of taking the design team to the children. For technologies where context of use is important, it may be more advantageous to have the design partnership occur in the contexts where children are more likely to use technology, which teams like Druin's have done(Chipman et al., 2006). At the same time, this makes logistics even more difficult, but less so if the adult members of a design team visit children in a place where they already go and may use technology (e.g., an afterschool program).

A tempting location to bring design teams is schools. This also comes with its own drawbacks: there are well-established power imbalances in schools that often prevent children from challenging adults' ideas and working with them as equals. In spite of this challenge, some researchers have tried design partnerships in schools, with Rode et al. introducing the concept of curriculum-focused design (Rode et al., 2003). This technique is a variant of Cooperative Inquiry that incorporates design and evaluations as part of lessons for students to include these activities into children's highly structured school days. Similarly, Pardo et al. encouraged the full participation of teachers in the design process (Pardo et al., 2005). Barendregt et al. added their experiences of including learning goals as part of participatory design activities in classrooms, which they found was difficult to do, but useful (Barendregt et al., 2016).

To summarize, children participating as design partners can have a significant positive impact on technology design, ensuring that their needs, abilities, and preferences are central to the design process. At the same time, there are many challenges to successfully partnering with children.

Adult roles during sessions with children as design partners

In order to organize and conduct design sessions, adult members of the design team have to fulfill certain tasks that go beyond participating in design activities (where the roles are equal to those of children). These tasks involve facilitating sessions, asking research questions, and documenting (Mazzone et al., 2010).

Perhaps the most important task in design sessions is their facilitation. A session facilitator leads design sessions, motivating both children and adults to participate, dividing them into groups if necessary, and ensuring that research objectives are met. Motivating and communicating with a seven-year-old and a tenured faculty member at the same time is no easy task. Thus, an important skill for facilitators to have is the ability to communicate comfortably with both adults and children.

Asking research questions is another task that needs to be fulfilled by adults, although occasionally children can fill this role. The facilitator is often the one to ask the research questions, which gives direction to the design session. Asking the questions requires knowledge of where the project is heading and what issues need to be addressed. Although a facilitator need not be involved in the daily activities of the project, the person responsible for asking research questions must be involved. In sum, facilitating provides the syntax for a design session, while asking research questions provides the semantics.

During and after a design session, it is important to document the process. Team members (which can sometimes include children) can take pictures, record video, and take notes during sessions. Lamberty and Kolodner reported on the positive effects of using a video camera as part of design activities with fourth grade children. Rather than being disruptive, the camera provided a way for children to give their opinions and ideas and provided designers with valuable information (Lamberty & Kolodner, 2005).

After design sessions, adult team members need to meet to discuss the outcomes of the session and make decisions about action items. At this point, note taking is also key to documenting the action items and conclusions reached through the session. Documenting the process ensures that no ideas are lost. It is also a way to keep track of where ideas come from and noting the evolution of design ideas. For academics, documentation is key for writing design briefings and sharing lessons learned through research papers and videos.

Personas

Personas are fictitious characters created to represent typical users of a technology. An early example of the use of personas in child-computer interaction came from Antle (A. Antle, 2003, 2004). While developing a web application for children on a short schedule, her team consulted children at key points in the development process. To fill the times in between, her team developed a set of personas that defined a set of representative children who were likely to use the technology. The characteristics of these personas were based on a number of factors, including the perceived characteristics of the children with whom the design team worked and relevant child development literature. The personas enabled the design team to question their design decisions from a different point of view. While not as effective as having real children give their opinions, personas can provide a way for design teams to consider issues from a child's perspective.

A later example of the use of personas comes from Wärnestål and colleagues. They discussed the use of child personas to help in the design of systems for vulnerable children (e.g., children suffering from cancer). In a pilot study, they constructed personas together with children, who were the intended users of the system. They developed the personas through four steps: focus groups, stakeholder interviews, design workshops, and modeling (Wärnestål et al., 2014). To better account for the social context of use of technologies, Abel and Grace proposed a framework for developing caregiver-child dyadic personas (Abel & Grace, 2020). Their framework emphasizes the relationship between caregivers and children. It is intended to enable the design of technologies that are compatible with caregiver-child interactions regarding interactive technologies.

A similar concept to personas is that of expanded proxy design. Metatla et al. used this concept to introduce children participating in design sessions to characters with characteristics representing children from marginalized or excluded communities, such as newly immigrant children and children with visual impairments

(Metatla, Read, et al., 2020). They found that these expanded proxies enabled participating children to be empathetic when designing for children who are different from themselves.

Beyond partnerships

Is it possible to go beyond the traditional notion of partnering with children, either as testers, informants, or designers? Ole Sejer Iversen and his colleagues at Aarhus University in Denmark have proposed that children take the role of protagonists by being empowered to not only shape the design of technologies, but also to reflect on the role of technology in their lives (Iversen et al., 2017). The child as protagonist approach involves the objective of children being the main drivers of design, an iterative and reflective process supportive of divergence and convergence of ideas and outcome measures that emphasize children's personal growth (Iversen et al., 2017). At this point other groups are beginning to replicate the approach (Iivari & Kinnula, 2018). A related approach proposes children as process designers, where they not only partner with adult designers during design sessions, but also become equal partners in decisions on what activities to conduct during the design process (Schepers et al., 2018).

The children as protagonists approach was preceded by work from the Aarhus University group on ecological approaches that shift emphasis from the technological artifacts that are produced to the ecologies in which technologies are integrated (R. C. Smith et al., 2013). These ecological approaches also involve looking at the emergence of social practices and meanings (as opposed to existing ones), the design of ecologies (as opposed to specific technologies), and the appropriations of technology through design and use. In addition, the authors propose three key dimensions to ecological inquiry: technology, social practice, and space.

These proposals for going beyond traditional design partnerships with children are based on previous experiences from this research group. Their experiences included the proposal of an alternative to Cooperative Inquiry called *BRIDGE* that involved children's participation, participation of all stakeholders, and grounding in children's everyday experiences (Iversen & Brodersen, 2008). This research group also reflected on the Scandinavian Participatory Design approach based on its values of democracy, skills, and emancipation (Iversen & Smith, 2012). Through a case study with teenagers designing an interactive museum exhibit, they described how the process affected power relations, project evaluation, and the final outcome. At the same time, the authors made the case that the end goal of Scandinavian Participatory Design is not necessarily a final prototype, but helping children realize that they have a choice in the design of future technologies.

Later, Iversen, and Dindler expanded the reflection with a discussion of how values, epistemology, and methodology need to align in order to truly shape tools and techniques. In a discussion of democracy, they considered enabling children to set research agendas. When considering skills, they proposed exploring alternative designs that arise from children's abilities (as opposed to what they cannot accomplish). Finally, in terms of emancipation, they again made the point of children having a choice in the technologies they use and design (Iversen & Dindler, 2013).

Design and evaluation methods

As mentioned earlier in the chapter, a typical lifecycle model includes activities to identify needs and establish requirements, design the technology, implement versions of the technology, and evaluate requirements, designs, or prototypes. Some researchers have identified variations for specific types of technologies, such as Rau et al. did for interactive learning systems (Rau et al., 2013). The following subsections include a discussion of the activities that can be conducted to achieve each of these goals. The only exception is in regard to implementing technology, as there is little evidence that technology developers use different tools (e.g., programming languages) to develop technologies for children than technologies for adults.

Identifying needs and establishing requirements

The first step in developing a technology is developing requirements for it. This step involves understanding the technology's users and stakeholders, the contexts in which the technology may be used, and what needs the technology should fulfill. Requirements differ from specifications in that specifications are concerned with how a technology accomplishes requirements. For example, a requirement might say that children should be able to customize their avatars, while a specification will say that they will first select the avatar's hair style, then the clothing. To enable freer design activities, specifications should come later in the design process.

Developing requirements is a very difficult task and, at the same time, a crucial one when developing technology. Mistakes in a set of requirements can lead to the wrong technology being designed and developed: one that does not meet the needs, abilities, and preferences of children. Hence, design teams should aim to iteratively refine requirements as the lifecycle progresses into more concrete prototypes and products.

As design teams develop requirements, it is important to organize them well, especially for large projects, to avoid having a large document that no one fully understands. Organizing requirements hierarchically, with a few high-level requirements and lower-level requirements providing more detail, facilitates everyone's understanding of the big picture and finding relevant requirements.

There are a wide variety of activities that design teams can pursue to obtain requirements. For children's technologies, there are often high-level goals that design teams want to pursue even before beginning activities. For example, they may know the target age group, context of use, pedagogical goal, and technical resources available, which some researchers have incorporated into tools to support this phase of the lifecycle (De Troyer & Janssens, 2014).

After determining high-level goals, there is a need to conduct activities to understand the children who are likely to use the technology and their context. Key stakeholders (e.g., parents, teachers) can often provide useful information to teams before working directly with children. However, there is no substitute for direct interactions with children, and if at all possible, these direct interactions should occur within the context in which the children may use the technology. Typical activities may involve observation and obtaining ideas by working with children in small groups.

An important aspect of any activity conducted with children is to empower them, as power imbalances can get in the way of obtaining useful information. One way of accomplishing this is to tell the children that the technology needs to work for children like them, and that they are experts at being children (while adults from a design team are not).

Sometimes there is a need to familiarize children and other members of the design team with novel technologies in order to develop requirements. While this is not as necessary as it used to be 20 years ago, it becomes necessary if a design team is using a technology that is not widely available. Technology immersion (Druin, 2002b), part of Cooperative Inquiry, is meant to expose design team members, especially children, to types of technologies they have not experienced. The exposure should be focused and guided by the team members experiencing it. The benefit to the children and other unfamiliar members is a new awareness of the potential of the technologies. The benefit to the rest of the team is a first look at how children might intuitively interact with such technologies. Technology immersion sessions are likely to occur toward the beginning of the design process. An example comes from Grufberg and Jonsson, who developed activities to involve 10- and 11-year-old children in investigating the sensors that are used in toys and videogame consoles. Once they achieved a deeper understanding of the sensors, children were able to generate ideas on how to use them (Grufberg & Jonsson, 2012). These activities could be considered a deeper form of technology immersion.

A variant on technology immersion is to use it to help the research team better understand how children interact with technologies they already use. In these situations, the adult team members immerse themselves in how children use these technologies. Such activities can inform the design of technologies by helping identify design features that work well and those that do not.

A similar activity that is useful for design teams to conduct as they develop requirements is a competitive assessment. A competitive assessment examines how well state-of-the-art technologies comply with the set of requirements compiled by the design team. In conducting research, competitive assessments can be accomplished through a literature review. In practice and in research, however, it is also useful to search for existing technologies that accomplish similar goals and to assess them against the set of requirements. Such an exercise can help identify ways in which existing technologies successfully implement requirements, ways in which they fall short, and any requirements that may be missing or may be unnecessary for the project at hand.

A type of activity that can help in assessing existing technologies and be used to evaluate prototypes later on, is contextual inquiry. Druin (Druin, 2002a) adapted this activity, originally devised to work with adults (Holtzblatt & Beyer, 1997), into her Cooperative Inquiry method. Contextual inquiry involves children and adults performing tasks while other adults and children observe them and take notes. The observers and the observed may switch roles. At the end of each session, the team identifies the positive and negative aspects of the interactions and suggests improvements. This is often accomplished with the help of sticky notes filled out as observations occur. As research teams develop prototypes, they can use contextual inquiry sessions to evaluate and improve them. These activities aid in eliminating design issues and bugs in the technology being developed.

Activities featured in research projects

The research literature provides examples of how children can be involved in developing requirements, included in this subsection. Some examples involve the activities described above. Others include alternative activities to identify needs and establish requirements.

One activity that children can undertake in order to help design teams obtain requirements is conducting interviews. For example, van Doorn et al. worked with children ages 9 to 12 as design partners. The children conducted interviews in the context of a project to design a playground that would bring children and older adults together. After receiving training on interview techniques, they interviewed both their peers at school and their grandparents. Based on this experience, they developed personas (see the definition earlier in this chapter) by working in small groups. The children took their work seriously and the personas they developed provided many useful insights (van Doorn et al., 2013). A similar idea had previously been implemented by Bekker et al., who developed a method in which the children played reporters and conducted interviews, wrote articles, took pictures, drew, and filled out questionnaires as part of the process (M. Bekker et al., 2003).

Sometimes it may be difficult for children to fully communicate about their contexts. To address this challenge, Dindler et al. presented a technique called Mission from Mars. In this technique, the researchers ask children to imagine that they are communicating with a Martian that would like to learn something about their lives (Dindler et al., 2005). Verhaegh et al. also used the Mission from Mars technique and found it very motivating for 7- to 10-year-old children (Verhaegh et al., 2006).

An example of an alternative way of conducting a technology immersion activity came from Williams et al. who conducted two workshops with 11- and 12-year-old children to assess the potential use of wearable computing by children. The children participated as informants in these workshops and were able to converse with researchers, but there was no elaboration of ideas (M. Williams et al., 2003).

When identifying needs and requirements, it may also be necessary to take a deeper look at the values of those participating in the design of a technology and those who may be affected by it. Flanagan et al. discussed ways of discovering and incorporating values, including the principles of the project, the designers, and the children, into software design for children (Flanagan et al., 2005).

Developing design ideas

Once requirements are well-developed, it is time to begin developing design ideas and specifications. The most common activity at this stage is the development of prototypes. These are mockups of interactive technologies that can be used to obtain feedback from children and other stakeholders. Developing design ideas usually begins with low-fidelity prototypes. Other activities may involve more basic brainstorming if there is less of a sense of what to build.

Low-fidelity prototyping involves the use of low-tech materials (e.g., paper, markers, other art supplies) to sketch out design ideas. This step can be very useful for obtaining basic design ideas at the beginning of the design process. As prototypes are developed, low-fidelity prototyping activities can aid the design team in designing interactions for new features to be added. These activities are meant to enable the design team to focus on the basic components of a technology. These include navigation through screens, the visual and verbal vocabulary to use, and the options users will perceive. It is usually better to stay away from more detailed prototypes, as they can often lead discussions to aesthetic issues that are best discussed later in the process.

Cooperative Inquiry (Druin, 2002a) makes use of low-fidelity prototyping. In Cooperative Inquiry's version of low-fidelity prototyping, children and adults divide into small teams to develop designs to address specific problems. These small teams should ideally be composed of two or three children and at least one adult. When working in these teams, adults and children voice their ideas and elaborate on them as they use low-tech prototyping materials to sketch them. These materials can include paper, markers, cardboard, crayons, tape, fabric, glue, socks, and so forth. At the end of a given session, all the teams come together and share design ideas. Derboven et al. provide recommendations for analyzing sessions of this type using both verbal (e.g., spoken words, writing) and tangible (e.g., sketches) products (Derboven et al., 2015).

It is possible to scaffold low-fidelity prototyping by setting it in the context of some pre-developed ideas if children do not have sufficient domain knowledge to develop ideas from scratch. An example of such an approach comes from Khaled and Vasalou in designing serious games with children (Khaled & Vasalou, 2014).

High-fidelity prototypes are interactive and provide more detail on the look and feel of a technology, although they can come in at various levels of fidelity. A first step may be computer-produced sketches (e.g., wireframes) that can provide more specific design elements and quick interactive navigation. These can be used to obtain more detailed feedback that can eventually lead to interactive prototypes that can go through more structured and thorough evaluations. For tangibles, three-dimensional (3D) printers can provide options for high-fidelity prototypes.

Sim et al. conducted two studies comparing evaluation results of prototypes of different fidelities for mobile games for children. In the first study, the fidelities included a sketch of the game on paper, screenshots of the actual game, and an interactive prototype on an iPad. In the second study, only sketch-like paper versions and the game on an iPad were included (Sim et al., 2016). The researchers recruited 7- to 9-year-old children for the first study and 7- to 11-year-old children for the second. In both cases, children rated user experience similarly and identified the same type of usability issues across fidelities. The results bolster the importance of conducting evaluations with low-fidelity prototypes for this type of game, since these prototypes are typically quicker to develop and easier to discard.

In a similar vein, Thang et al. compared the use of brainstorming and prototyping activities with 8- to 12-year-old children. They found that children developed more creative (i.e., surprising, novel) solutions when using brainstorming methods, and that prototyping sessions tended to yield more relevant and workable ideas (Thang et al., 2008).

Regardless of the type of prototyping used, there are design ideas that may occur in patterns. Eriksson et al. pursued this idea by identifying gameplay design patterns and using them to guide co-design activities with children to redesign a collaborative game (Eriksson et al., 2019). This approach helped the design team analyze observations, supported children's involvement, and provided the team with a common vocabulary.

As design teams develop ideas and evaluate them, requirements must often be changed. Ideally, the process should involve sets of iterations that result in increasingly complex prototypes, eventually leading to the development of a final version of the technology.

Some researchers have argued for maximum flexibility in ordering activities. For example, Stringer et al. proposed that the order of activities should be customized to each specific project. They identified four types of activities: technology introduction (similar to technology immersion), problem statement, generation of ideas, and research results (Stringer et al., 2006).

Prototyping examples from research projects

Many projects have featured examples of the use of prototyping techniques. One of the most common ways of developing low-fidelity prototypes is through sketching. Chen et al. worked with 10- and 11-year-old children to develop web-based user interfaces for community websites, asking the children to develop layouts for web pages. An evaluation comparing the user interface developed out of this activity found it to be more usable than a popular commercial user interface (C.-H. Chen et al., 2004).

Another form of low-fidelity prototyping is storyboarding, where the way a technology may be used is sketched out as part of a story, often in comic book format. Moraveji et al. reported on the successful use of comics as a way to elicit design ideas from children. They found that if children get to fill in the blanks in comics that have a beginning and an end, they are likely to produce more ideas than if they are given blank pages to do traditional storyboarding (Moraveji et al., 2007). Isomursu et al. also used storytelling activities to obtain design ideas through web-based tools (Isomursu et al., 2004).

A challenge when working in design teams is elaborating on previous low-fidelity prototypes, especially those made with art supplies. To address this challenge, Walsh et al. introduced *layered elaboration*, a technique that can be used when partnering with children in design. Layered elaboration enables children to develop previous sketches further by adding more details or replacing parts without having to redraw them. The simplest way of using this technique is to begin with a paper sketch and augment it through the use of layers of transparencies, which can be used to modify the original sketch (Walsh et al., 2010).

Another challenge for design teams is remote collaboration, in particular for geographically distributed design teams. Walsh et al. presented *DisCo*, an online tool to support remote, asynchronous design partnerships between children and adults. *DisCo* enabled design partners to iterate prototypes, annotate them, and communicate with each other. *DisCo* included an area for drawing prototypes and an area for annotations, with the drawing area enabling the use of layers to facilitate elaboration of prototypes (Walsh et al., 2012). Experiences with *DisCo* and iterative development of the tool led to the design of an *Online Kidsteam* environment with a set of tools for remote collaboration (Walsh & Foss, 2015). Further research on online collaboration tools involved the use of existing three-dimensional environments, such as *Roblox* and a *Minecraft* clone called *Minetest,* to support remote design both synchronously and asynchronously (Walsh et al., 2016).

Sometimes it is difficult to gain appropriate feedback from low-fidelity prototypes. For example, de Valk et al. and Soute et al. worked on the development of technologies to support children's open-ended play (de Valk et al., 2013; Soute et al., 2013). The devices they planned to use provided feedback primarily through audio and tactile means (in addition to LED lights), which made visual sketching of limited use. Likewise, given that the games they wanted to support were fast-paced (e.g., similar to tag), it was difficult to obtain feedback from noninteractive prototypes. They therefore proposed quickly developing working prototypes and trying them out in actual play situations.

Most of the methods described in this section were developed to design either visual or tangible technologies. Fitton et al. explored methods for designing voice user interfaces. In their work with 14- and 15-year-old children, they found a combination of scripting exchanges on paper followed by high-fidelity prototyping on a tablet with speech output worked well to develop design ideas (Fitton et al., 2018).

Ideas from existing technologies

There are other situations where the question is how to best use existing technology. Garzotto discussed an experience working with twenty-four 10- to 11-year-old children at a school over three months. In this case, the children and researchers partnered to understand how to best use an existing tool within an educational setting with specific goals in mind (Garzotto, 2008).

Another approach that is sometimes used for developing ideas is to hold workshops. Williams et al. presented an example of working with children as informants to develop and obtain feedback on mobile devices augmented with GPS that could be used by children to tag locations with sounds (M. Williams et al., 2005).

Specific populations

While a majority of the research outlined above involved typically developing elementary school children, some researchers have developed design ideas for other groups of children. If these groups include vulnerable or marginalized children, there can be complex ethical considerations to consider as outlined by Spiel et al. (Spiel et al., 2018).

Preschool children

When it comes to children younger than elementary school age, Wyeth and Purchase emphasized the need to take into account the literature on developmental psychology when forming concepts for the design of technologies. They proposed design principles based on recommendations for children in Piaget's preoperational stage (under 7 years old). These included supporting open-ended and discovery-oriented activities, child-initiated play, active manipulation and transformation of physical items, easy ways to get started, increased challenges for better skills, and the opportunity to create something (Wyeth & Purchase, 2003).

Guha et al. extended Cooperative Inquiry by developing a new set of activities to enable children ages 4 to 6 to join a design team as design partners. The new set of activities was necessary due to children in this age group being typically more egocentric than older children. They recommended methods for incorporating ideas from many children in order to make them feel involved in the design process (Guha et al., 2004).

Also considering preschool children's developmental milestones, Superti Pantoja et al. developed a method called play-based design (Superti Pantoja et al., 2020). The method, intended for the design of tangible or embodied technologies, uses stories to set a physical and social context for design and involves children role-playing as characters in the story while using generic props to stand for items including technology. The authors used the method with 3- and 4-year-old children finding that it enabled children of both ages to contribute design ideas through an enjoyable, developmentally appropriate activity.

Joly et al. presented their experience conducting card sorting activities with 3- and 4-year-old children. Card sorting is a commonly used technique with adults that involves sorting cards that represent bits of information or web pages into piles. It is most often used to develop the information architecture of a website. Joly et al. asked children to categorize cards into pre-established categories. Cards that fit into well-known categories (e.g., superheroes) were much more likely to be classified correctly than cards that fit into more abstract concepts such as "make" and "do." The authors concluded that the method could be used to learn whether children could understand specific categories, for example, categorizing different types of activities available in an app (Joly et al., 2009).

Marco et al. discussed design experiences with 3- to 6-year-old children who participated in the development of tangible interaction toys for use on an interactive tabletop. The design process included the creation of user profiles (i.e., sets of user characteristics), Wizard of Oz techniques, and peer tutoring (i.e., children teaching other children how to use a technology) (Marco et al., 2010).

Teenagers

In addition to design ideas developed for elementary school children, there have also been design activity ideas developed for teenagers. Poole and Peyton shared their reflections on best practices for conducting research with teenagers. For example, to address issues of retention in longitudinal studies, the researchers cited factors that make it more likely that teenagers will continue participation, including parental encouragement, peer influence, friendships, and understanding how their participation in research can make a contribution to society. To address power imbalance issues, they recommended researchers working with teenagers use casual introductions, dress informally, make references to popular culture, and remind teenagers of the importance of their opinions (Poole & Peyton, 2013).

Knudtzon et al. (2003) used Cooperative Inquiry activities with 10- to 13-year-old children and found the activities had to be adjusted to be more similar to those used with adults in participatory design (Knudtzon et al., 2003). Bonsignore et al. also used participatory design activities with a large number of 13- to 17-year-old gamers to develop design ideas for an alternate reality game, finding these activities resulted in identifying novel design elements for the game (Bonsignore et al., 2016).

Read et al. explored the meaning of “cool” to teenagers through an activity at a school. They found that preferences appeared to vary by gender and age, and included facets such as supporting rebelliousness and anti-social attitudes, retro-looking items, authentic devices (e.g., known brands), expensive devices, and innovative items (J. Read et al., 2011).

Another example of the use of participatory design techniques from teenagers emphasized not only design outcomes, but learning outcomes for the teenagers. These learning outcomes included appreciation for the group in which they worked, metacognitive awareness of learning, development of academic and professional identities, and visualization of learning pathways (A. Bell & Davis, 2016).

Children with disabilities

Another group of children who may require a different approach are children with disabilities. Benton and Johnson provide an overview of the involvement of children with disabilities in the design process as part of research projects, finding a wide range of approaches and levels of child involvement, as well as a diversity of roles played by adults, including stakeholders (Benton & Johnson, 2015).

The population that has gained the most attention in the past few years has been children diagnosed with autism spectrum conditions, with typical design activities for this population requiring greater involvement from adults (both researchers and other adults children trust, such as caregivers) when compared to similar activities conducted with typically developing children, and few experiences including groups of children with mixed abilities (Börjesson et al., 2015). Benton et al. presented methods (*IDEAS*) and a framework for involving neurodiverse children (mostly diagnosed as being on the autism spectrum) in the design of technologies by focusing on their strengths. The framework calls for structuring the environment where design activities take place, providing supports by understanding the preferences of children diagnosed with autism, and tailoring the environment and the supports to the needs of the participating individuals (Benton et al., 2012, 2014). Most of the other methods used with similar populations are compatible with these ideas.

Frauenberger, Spiel, and the rest of the team behind the *OutsideTheBox* project (Frauenberger, Spiel, & Makhaeva, 2019) have focused on providing greater agency to children diagnosed with autism, arguing for the design of technologies that matter to the children, rather than those that matter to the adults in their lives (Spiel et al., 2019a). The *PEACE* approach to evaluation instantiates this perspective, engaging children diagnosed with autism directly in defining goals and methods and data gathering and interpretation, with the objective of ensuring that what is considered a successful technology is compatible with the perspectives of the children involved in the process (Spiel, Malinverni, et al., 2017). The same team described similar approaches, always giving primacy to the children's perspective (Frauenberger et al., 2016, 2017; Frauenberger, Spiel, Scheepmaker, et al., 2019; Spiel, Frauenberger, & Fitzpatrick, 2017; Spiel, Frauenberger, Hornecker, et al., 2017; Spiel, Malinverni, et al., 2017), which they suggest is often missing from other research projects (Spiel et al., 2019b).

Wilson et al. contributed design methods for co-designing with children diagnosed with autism who are minimally verbal. They describe design processes for the design of tangible devices. They refer to the method they developed as *Co-Design Beyond Words* (CDBW), which focuses on constantly paying attention to children's behavior to obtain feedback from them, for example, through changes in engagement, transitions, and disruptions. They point at three phases to CDBW: the foundation phase where researchers become very familiar with individual children, the interaction phase where researchers obtain behavioral feedback on prototypes, and the reflection phase where researchers may review videos of sessions and reflect on lessons learned (Wilson et al., 2019). Further work by the group identified modalities of self-expression that are relevant to co-design for this group of children(Wilson et al., 2020).

In terms of specific methods, Hourcade et al.'s design activities included work with children diagnosed with autism who were able to understand speech, but rarely, if ever, spoke. With this group of children, they obtained feedback by asking the children yes/no questions, which were answered through pointing to pieces of paper with the words "yes" and "no" on them. With children who could express their opinions verbally, it was not a problem obtaining ideas and feedback from them through Contextual Inquiry activities, although sometimes there was a need to work with one child at a time. This research also included design activities with mixed groups of children including typically developing children and children diagnosed with autism spectrum disorders (Hourcade, Bullock-Rest, et al., 2012).

Malinverni et al. also presented their experiences conducting participatory design sessions with children diagnosed with autism within the context of designing a game. They found that going back to the basic game narrative helped motivate and focus children. The researchers made use of individual boxes where children could keep their previous design ideas, which were also useful for referencing previous work (Malinverni et al., 2014). Fletcher-Watson et al. focused on user-centered design approaches with stakeholders rather than children, given that their target user group was preschool children diagnosed with autism. Their design process was followed by an implementation of the tool and an evaluation with 41 children (Fletcher-Watson et al., 2016).

Another team that worked with children diagnosed with autism, Frauenberger et al., discussed the design of a tool to support children providing feedback on working prototypes. The tool enabled children to associate an emoji with what they were experiencing, in order to show approval, or to comment on it. The tool was overlayed on the top left of a large touchscreen that enabled interactions with the system being critiqued. Some of the children who used it also appropriated it for emotional self-regulation, using repetitive behaviors to calm down (Frauenberger et al., 2012, 2013).

Metatla's research group has focused on conducting design experiences with elementary school-aged children with mixed visual abilities, staying mindful of the fact that children with visual impairments increasingly attend mainstream schools. Their experiences have included co-design activities with small groups of children that include children with visual impairments and sighted peers. The activities included the use of art supplies for low-fidelity prototyping and bodystorming (Cullen & Metatla, 2019; Metatla, Bardot, et al., 2020; Metatla & Cullen, 2018).

Sharma et al. presented their design experiences focusing on empowerment issues with 17- through 40-year-old people with a variety of disabilities. They learned about the importance of stakeholder participation (e.g., parents and teachers), the mediating factor of communication ability, difficulties with participants making fun of each other, and the importance of conducting research in a location where the children already participate in educational activities (S. Sharma et al., 2020). Holone and Herstad discussed common challenges in conducting participatory design sessions with children with severe disabilities. They identified tensions, such as rapid prototyping versus the need for time to communicate, the need for active participation versus lack of comfort in an unusual role, and direct communication versus communication with proxies (Holone & Herstad, 2013).

Sometimes it may be difficult for an entire design team to have access to children with severe disabilities. To address this limitation and explore novel ways of designing for children with such disabilities, Ibrahim et al. explored the creation and use of design documentaries, which aim to vividly convey children's experiences while not requiring the entire design team to witness them directly (Ibrahim et al., 2020).

Marginalized and low-income children

There may also be challenges when interacting with children from a different culture than that of the adults in the design team, especially if they come from communities with low socioeconomic status. Fisher et al. presented on their experience conducting design activities in a refugee camp with Syrian youth (Fisher et al., 2016). The activities, conducted with help from staff from Non-Governmental Organizations working at the camp and volunteers, involved developing paper sketches of technologies for the youth to help their families. The activity yielded valuable information to better understand young people's views on their challenges, including those related to information and communication technologies (Fisher et al., 2016).

Hamidi et al. discussed their experience conducting design workshops with children in a disadvantaged area of Oaxaca, Mexico (Hamidi et al., 2014). They made an emphasis on the importance of establishing trust through local contacts, incorporating relevant cultural and social elements, planning concrete outcomes, and using technology appropriately.

Earlier, Hourcade et al. generated recommendations for developing technologies for marginalized children based on a workshop held at the 2010 Interaction Design and Children conference (Hourcade et al., 2010). They recommended engaging with community-based organizations already working with children, partnering with marginalized people in design, and training local people from marginalized groups so they can become research leaders.

Also working with low-income children in low-income regions, Kam et al. faced the challenge of not being able to communicate directly with the children with whom they worked in a rural setting in India. They observed issues with local power structures, recommended getting help from locals who could translate and help understand cultural issues, and found that they were able to get better feedback from high-fidelity than low-fidelity prototypes (Kam et al., 2006). Ramachandran et al. extended this work by relating additional experiences that highlighted the value of local stakeholders and social network structures in the successful design and deployment of technologies (Ramachandran et al., 2007).

Evaluation

Evaluations of technologies for children can take many forms. The following subsections include a discussion of evaluation frameworks and the main methods, including informal evaluations, expert reviews, usability testing, and field studies.

Evaluation frameworks

Markopoulos and Bekker developed a framework to assess usability testing methods with children (Markopoulos & Bekker, 2003). They established three dimensions to consider: the criteria to assess the methods, the characteristics describing the methods, and the characteristics of the children being tested. In terms of criteria for assessing the methods, they mentioned robustness, reliability, validity, thoroughness, and efficiency. The characteristics for method descriptions included number and grouping of participants, evaluator, context, procedure, data capture, and tasks. Finally, the children could be characterized in terms of verbalization, extroversion, gender, concentration, thinking skills, trustworthiness of self-report, knowledge, and age.

In a similar effort, McKnight and Read proposed a framework for evaluating technologies with children. It makes distinctions between evaluating for playing (considering fun, entertainment, and experience), for learning (considering pedagogy, effectiveness, and learning outcomes), and for using (considering usability, accessibility, and efficiency) (McKnight & Read, 2011).

Markopoulos et al. published an entire book on the topic of evaluation methods that can provide more details than those provided in this section. In particular, it provides more detailed explanations of methods and how to select them (Markopoulos et al., 2008).

Informal evaluations

The most common form of evaluation, if a design team has access to children, is to conduct informal evaluations in which children can provide feedback on requirements, design ideas, or prototypes. This type of evaluation requires little planning and can provide useful information throughout the design process. Contextual Inquiry techniques, described earlier in this chapter, can be one way of obtaining informal feedback.

Rick et al. discussed an example of obtaining informal feedback from low-fidelity prototypes used for the design of tabletop apps. In one example, the researchers used small boxes with pictures on one side to take the place of the digital representations of objects children would be able to manipulate on the screen. Another example made use of cardboard cutouts with pictures on them that again represented the items that could be manipulated on the tabletop. Overall, the low-fidelity prototyping techniques worked well, especially because they had similar affordances to the target device. Challenges arise with this technique when affordances not present in the interactive tabletops are present in tangibles. For example, children cannot lift a digital item off an interactive tabletop (Rick et al., 2010).

Expert reviews

If children are not available, adults can identify problems with a user interface through expert reviews. These are typically conducted by consulting a set of heuristics. The experts can then navigate through the user interface of a technology designed for children to see if it complies with these heuristics. Expert reviews can be very useful in quickly identifying usability issues before conducting more formal evaluations.

Baauw et al., for example, explored whether expert reviews could work for children's technologies by evaluating the use of a predictive evaluation method. The method, called Structured Expert Evaluation Method (SEEM), involved the use of checklists by experts to predict problems in educational games. They found this method could uncover most usability problems, however, expert reviews identified issues that did not turn out to be usability problems when 9- to 11-year-old children tested the same games (Baauw et al., 2006). Bekker et al. followed this research by comparing SEEM to the Combined Heuristic Evaluation (HE), another form of expert review. Through a study, the researchers found that SEEM worked better than HE both in terms of thoroughness (finding more problems) and validity (finding true problems). SEEM provided evaluators with more guidance when predicting problems (M. M. Bekker et al., 2008).

Brandão et al. used another method for expert reviews called the Semiotic Inspection Method, which is an expert review method that places an emphasis on evaluating communication between the user and the system, and was originally developed for systems with adult users. The method involves studying areas such as instructions and help (referred to as metalinguistic signs), how the system's state is presented (referred to as static signs), and how transitions between states are communicated to users (referred to as dynamic signs) (Brandão, Trevisan, et al., 2010).

Usability testing

Usability testing is perhaps the most common form of formal evaluation for user interfaces across all user populations. It typically involves selecting a set of tasks that are representative of use of the technology and asking users to complete them, if possible, while thinking aloud. Thinking aloud can provide useful information by letting the design team learn about users' thought processes as they complete tasks. Usability testing sessions are usually audio and video recorded in order to later code behavior and measure user performance based on usability goals such as accuracy and efficiency. After completing tasks, users typically fill out questionnaires and/or participate in interviews, which may be used to understand user experience and preferences. All activities generally occur in a controlled lab environment with no distractions, where the conditions are kept the same for every participant.

Children working together during usability testing is a recurring theme in research projects. For example, Als et al. compared usability evaluation techniques and found that pairs of 13- and 14-year-old children who knew each other identified more usability problems with less effort than pairs who did not know each other and more effort than children thinking aloud as they used software individually (Als et al., 2005). In the same vein, Hanna et al. recommended that pairs of children participate in evaluations together without an observer being present, and that they pair children with good friends (Hanna et al., 2004). Höysniemi et al. successfully used peer tutoring, where one child taught another how to use the system, as a way to evaluate the usability of a system through its teachability and learnability. They tried peer tutoring with children ages 5 to 9 who taught other children how to play a game (Höysniemi et al., 2003).

Following the social theme, Fransen and Markopoulos explored the use of a social robot to elicit information from children, encouraging them to verbalize their thoughts and feelings to the robot. The reason for the approach is the difficulty many children have following traditional usability testing protocols, such as “think aloud.” The researchers went through three iterations of the protocol to learn how actively the robot should intervene, how to provide visible emotional cues through the robot, and what type of dialogue to use (e.g., what to ask, how to help, how to acknowledge the child). In a comparison with conducting usability testing with an adult, children preferred the robot, but also saw it as extra work to communicate with it (Fransen & Markopoulos, 2012).

Comparing social and individual usability methods, Van Kesteren et al. assessed six methods to see which elicited more verbal comments from 6- and 7-year-old children. They found the most verbal comments were obtained in active intervention sessions when researchers asked questions during tasks. They did not find co-discovery sessions, where pairs of children work together, to work as well. Other techniques worked better, such as think-aloud, retrospection (a child reflecting on their usability session by watching a video of it), and peer tutoring (van Kesteren et al., 2003).

Following adult-oriented methods, Donker and Reitsma conducted usability testing of software to build literacy skills with 5- to 7-year-old children. They found that they identified most problems by observing the children’s behavior and that thinking aloud helped mainly in assessing the importance of the problems (Donker &

Reitsma, 2004).

It may be more difficult to conduct usability testing using adult-oriented methods with younger children. Egloff reported on challenges conducting usability studies with preschool children, finding it was difficult because the children in the study could not conduct a task for very long, tried to please adults, were easily distracted, and had difficulty expressing their likes and dislikes. Creative alternatives are likely to yield better results (Egloff, 2004).

Physiological data (i.e., from body sensors) has also been suggested for use during technology evaluations. Sridhar et al. piloted use of skin conductance and heart rate data together with observations and self-reports from kindergarteners as they participated in learning activities in order to estimate their cognitive-affective states (Sridhar et al., 2018). It is important to note that other researchers in the child-computer interaction community have expressed concerns about invasive data gathering and the quantification of children (Hourcade et al., 2018).

Questionnaires

There has been a significant amount of research on self-reported measures, such as questionnaires. These are typically filled out after completing tasks with a technology, or they can be administered on their own. Thinking of how to deliver questionnaires, Kano and Read studied the interchangeability of paper and computer questionnaires for children. The study's participants were children between the ages of 8 and 9. The results, based on questionnaires asking children about their computer experience, suggest that children can use both types of questionnaires and can answer questions consistently in both types of media (Kano & Read, 2012). Milne et al. developed an earlier version of an online questionnaire for children (S. Milne et al., 2003).

As discussed in the *Usability and Children* chapter, one issue of importance for children beyond usability is fun. MacFarlane et al. studied the relationship between usability and fun measures. They found that there were positive correlations between the two based on observations of children as well as children's own assessments of software. They also found that the assessed usability and fun differed depending on whether they were obtained by observing children or by children's reports. Another interesting result was that scale ratings using a *Smileyometer* (a set of five emojis going from "awful" to "brilliant") were not particularly useful as most children were overly enthusiastic about all the software titles they tried. Instead, more interesting data was gleaned from asking the children to rank the titles based on different characteristics (MacFarlane et al., 2005).

Continuing this line of work, Read reported on validating the *Fun Toolkit*, a survey instrument for measuring children's opinions of technology. The *Fun Toolkit* includes use of the *Smileyometer*, the *Fun Sorter* to compare and sort a set of technologies, and the *Again Again* table, in which children can say whether they would like to use a technology again (J. C. Read, 2008).

Sim and Horton reported on a study comparing the *Fun Toolkit* to the *This or That* method for the evaluation of games for children. The evaluation, with 7- and 8-year-old children, found that both methods could be used to establish preferences for games and yielded similar results (Sim & Horton, 2012). Sim et al. used the same two methods to evaluate a serious game in Uganda, finding the need for adjustments for a different cultural context given some low reliability scores (Sim et al., 2015). Zaman et al. conducted a similar study, this time comparing the *Smileyometer* to *This or That,* with 113 children ages 33 to 90 months (Zaman et al., 2013). *This or That* worked well for measuring preferences and was reliable for children who were at least 4 years old. The *Smileyometer,* on the other hand, was not as reliable, as extreme positive scores were overrepresented and results were inconsistent with actual product preferences. Research conducted by Hall et al. suggests that using a scale that includes only smiley faces (excluding sad faces) appears to address the *Smileyometer's* limitation (L. Hall et al., 2016).

Following a similar approach, Dietz et al. developed the *Giggle Gauge* to evaluate children's engagement with technology. They validated this questionnaire with 4- to 7-year-old children, confirming its validity and reliability (Dietz et al., 2020).

Using a creative alternative to traditional survey instruments, Xu et al. (2009) asked children to draw visual representations of their experiences with technology with the purpose of evaluating technologies. The researchers then coded the drawings looking for fun (e.g., smiling, fun words), goal fit (e.g., user control, competition), and tangible magic (e.g., feel of the interface) (D. Y. Xu et al., 2009). On a similar note, Gourlet presented work on the use of "emotional imprints," ink-based visual representations that children could make using color to represent emotions. Gourlet used these imprints to learn about children's emotions with respect to technology use in a classroom (Gourlet, 2018).

Interviews

Usability testing often includes the use of interviews after or in lieu of questionnaires. One technique used for interviews is laddering (Zaman & Abeele, 2007). *Laddering* is an in-depth interviewing technique with corresponding methods for quantitative data analysis. Interviewers ask children about product or technology preferences and to explain their preferences based on technology attributes, how these attributes help achieve children's goals (referred to as consequences), and how these goals fulfill children's needs or preferences (referred to as values). Quantitative analysis can be used to develop a hierarchical value map, which includes attributes, consequences, and values. Zaman and Vanden Abeele conducted a laddering study with children aged between 33- and 86-months-old, and found that the techniques worked well only with those aged 5 or older (Zaman & Abeele, 2010).

Price and Jewitt presented methods for interviewing children about embodied interactions in the context of using a tabletop application. They explored semi-structured interviews, semi-structured interviews with video recall, and interviews using the embodied technology. They found they received different kinds of information with the different approaches, with video recall helping interviewers probe specific events, and having the technology present during the interview making it easy for children demonstrate as they spoke (Price & Jewitt, 2013).

Field studies

The wide use of mobile devices has brought challenges to traditional usability testing, as it is difficult to replicate field conditions in a lab. For this reason, field studies are becoming more common, with technologies tested "in the wild." While the controlled conditions are lost, mobile devices enable tracking of every interaction and even the location of users, thus providing a wealth of data. It is usually a good idea to conduct usability testing first to address any usability issues that can be identified in the lab. Once a technology works well in the lab, field testing can identify further problems that may only occur in the field.

Another reason for field testing is situations where the context of use is very important. Robertson et al. (2012, 2013) discussed the importance of evaluating educational technology in classroom contexts. They proposed a model called *Train the Teacher Model* to deploy and validate educational systems. The model involved partnering with teachers by providing initial training and ongoing support during technology deployment. The researchers found that this approach helped researchers with obtaining more valuable data, and teachers and students in getting the most out of the technology (J. Robertson et al., 2012, 2013).

One method for obtaining more informal feedback from field deployments, but that could also be used in earlier stages of development, is audio journaling. Given the wide availability of mobile devices with audio recording capabilities, this is an accessible method that can provide useful feedback to design teams, while enabling child participants to engage in self-reflection, as noted by Sawhney et al., who have used this method in multiple projects around the world (Sawhney et al., 2018).

Summary

The choice of appropriate methodologies is critical for successfully designing technologies for children. These methodologies can be applied through all phases of design and development, including identifying needs and establishing requirements, designing the technology, implementing versions of the technology, and evaluating requirements, designs, or prototypes. From the field of software engineering, the main lesson learned is the need for iteration through these development phases, and flexibility in order to accommodate change. From human-computer interaction, the main lesson learned is the need to engage users and other stakeholders, if possible, in every phase of development (usually with the exception of the implementation phase).

Allison Druin classifies children’s engagement at four levels: user, tester, informant, and partner. A majority of the research in child-computer interaction engages children either as informants or partners. In both of these cases, children provide feedback and ideas throughout the development process. As informants, they do so at key points in the design process, while as partners, they join the design team and participate equally in all design decisions.

Researchers have shared experiences on using a wide variety of methods for each phase in the design process. For obtaining requirements, common activities include observation, interviews, and participatory design activities with children and stakeholders, preferably conducted in the contexts where children are expected to use the technology.

For developing design ideas, the most common activities include brainstorming and the development of prototypes of various fidelities. Earlier in the process, prototypes are more likely to be low-fidelity, usually put together from art supplies. These can be designed working together with children, as the materials used are accessible to them. Later on, design teams may develop interactive prototypes to test more detailed interactions. There are a wide variety of approaches to designing prototypes and deciding which one to use often depends on the type of technology being designed, the characteristics of the children who will use it, and the context in which it will be used.

Evaluation methods include those used for informal evaluations, expert reviews, usability testing, and field studies. Informal evaluations typically involve feedback from children through activities that usually do not require much planning. A useful method for these purposes is Contextual Inquiry, which was originally developed for adults, and involves children using the technology (or prototype) while the researchers observe and take notes on likes, dislikes and aspects to change.

Expert reviews are based on sets of heuristics, with experienced designers evaluating a technology or prototype without input from children. These reviews can be useful to remove any obvious problems before conducting evaluations involving children. Researchers have successfully used methods such as the Structured Expert Evaluation Method (SEEM) and the Semiotic Inspection Method.

Usability testing is a formal method for evaluating technologies or prototypes. This method involves selecting a relevant and representative set of tasks for children to conduct with the technology. Design team members ask children to conduct these tasks in a controlled environment with no distractions, where their actions and speech are recorded. After the children complete the tasks, design team members may interview children or ask them to fill out questionnaires. Much of the research with respect to usability testing involves identifying methods that make it more likely that children will express their opinions about technology. There has also been research on self-reported measures, such as questionnaires, as well as research on interviewing techniques.

Field studies are best suited for mobile technologies, or technologies that need to work in particular environments, such as classrooms. The methods in this case often involve using the logging capabilities of devices to track how technology is used and in what context, as well as the use of video and audio recordings.

Together, these methods provide design teams with a toolbox of activities to pursue as they design technologies that are a good match for children’s needs, abilities, preferences, and contexts of use.

Chapter 7
Creativity and Problem Solving

Recent child development theories that include the concept of embodiment, rather than focusing solely on the child's brain, propose that as children develop, it is their brains, bodies, and environment that change and develop together. Hence, positive development outcomes may be more likely in richer environments that can afford greater manipulation, provide creative outlets, and enable the construction of artifacts in a social context. For this reason, much of the activity-based focus in the design of technologies for children involves creative endeavors, such as programming and storytelling.

This chapter provides a summary of research on technologies to support and enable children's creative activities. It begins with programming, arguably the first dominant creative activity set up for children using computers. It continues with a neighboring topic, the maker movement. Next is a discussion of research on storytelling technologies, where the focus has been on enabling children to express themselves in novel ways. This leads to another set of activities where technology has been used to support children's creativity: performance authoring and support. The last area of creativity covered in this chapter is the novel opportunities technologies provide for children's play.

Programming

The origins of the field of child-computer interaction can be traced back to Papert and others' work at the Massachusetts Institute of Technology (MIT) on making programming accessible to children. One of the main motivations behind this line of research was the idea that through programming, children could learn mathematical and logical concepts while creating artifacts of interest. These efforts led to children's involvement with computers at schools to be mainly directed at programming activities throughout the 1980s and part of the 1990s. The focus on programming activities was later replaced by educational games, multimedia activities, and web-based interactions. In spite of this change, much research is still being conducted on providing children with programming tools that fit their needs and abilities. In fact, during the 2010s there was a resurgence of calls for bringing back programming to primary and secondary schools, with recent examples including countries such as Uruguay (Miños Fayad, 2014) and the United Kingdom (Cellan-Jones, 2014). These government initiatives have, in turn, sparked a wide set of alternatives for children to engage with programming and computing (Yu & Roque, 2018).

Over the years, the emphasis has gone from text-based programming environments, to visual programming, to tangible and even room-based programming environments. The following subsections outline research efforts under each of these approaches.

Text-based programming

Most of the early experiences with programming languages for children were text-based, in that the programs consisted of text, and children had to type in text to write their programs. This was true even in cases where there were other available tools to create media within the programming environment.

The first widely used programming language designed for children was *Logo* (Papert, 1993), which had several versions, including a more visual approach in *MicroWorlds* (Vincent, 2002).

An example of research with *Logo* comes from Harel and Kafai, who collaborated on projects where children from diverse backgrounds used *Logo* to design educational software to teach fractions to younger children (Harel, 1991). Some of this work involved collaborating with peers as well as helping younger children with their own programming activities (Y. Kafai & Harel, 1991). The child programmers learned about fractions by having to think about how to design software to teach fractions (Harel, 1991). Kafai continued a similar line of work, providing children with tools to create games for teaching fractions (Y. Kafai, 2001; Y. B. Kafai et al., 1995), and instructional software to learn science concepts (Y. B. Kafai & Ching, 2001).

Another example of *Logo* use came from Subhi who studied 8- and 9-year-old children's use of an Arabic version of *Logo* and recommended that children program in pairs to reduce the need for teacher intervention, and that they formulate their own goals in order to increase motivation (Subhi, 1999).

In spite of these positive results, there was a controversial change away from programming in school use of computers in the 1990s. Robertson, for example, was concerned that the move from children programming to children accessing multimedia content could get in the way of children experiencing a high level of control over and interaction with computers (J. Robertson, 1998). Similarly, O'Reilly argued for the incorporation of programming as part of the curriculum given that it provides opportunities for making use of logical and mathematical knowledge in activities where children can pursue their own goals (O'Reilly, 1998).

Part of the reason for the move away from programming was the difficulty many children faced in producing complex programming constructs. Many research efforts have been undertaken to alleviate this problem. Bruckman and Edwards studied 6- to 16-year-old children's use of a programming environment using natural language (i.e., English). The approach seemed to appeal mostly to children 8 and older, while the children who went beyond a basic level of scripting were 10 or older. The researchers' conclusions were positive toward the use of natural language programming by children with the purpose of promoting learning (A. Bruckman & Edwards, 1999). Wright and Cockburn on the other hand, found that 11-year-old children understood algorithms more quickly if they saw them in conventional code than if they saw them in English. There were no differences in terms of accurately interpreting the algorithms (Wright & Cockburn, 2005).

Even though textual programming has recently fallen out of favor, in particular with younger children, it is still widely used in introductory computer science courses for children in their teenage years. It can also provide advantages over visual programming for children with visual impairments. Kane et al., for example, developed *Bonk*, an accessible text-based programming environment specifically for children with visual impairments. *Bonk* enables children to develop audio games (Kane et al., 2018).

Visual programming

To address the difficulties of using text to program, many research groups began exploring visual methods of programming that often involve text but make attempts to reduce typing to avoid problems with syntax and favor children recognizing programming constructs instead of having to recall them. These efforts have been further enabled by the wide availability of higher-quality displays.

An early effort on visual programming, put together by Apple, was called *KidSim*. Rader et al. evaluated children in fourth and fifth grade using *KidSim* and found that children were able to complete simple tasks with the environment such as drawing and animating characters, but were not able to construct more complex behaviors (Rader et al., 1997).

Many other projects began in the mid to late 90s, including *Squeak* (Ducasse, 2006), which enabled children to program in a visual version of the foundational object-oriented language *Smalltalk*. *Alice* was also conceived to teach object-oriented programming, albeit originally for undergraduate students (Cooper et al., 2000). Since then, it has spawned descendants aimed at younger audiences.

Perhaps the best-known current example of visual programming is *Scratch* (Resnick et al., 2009), which enables children to select from categorized sets of instructions that can be dragged into a programming area and attached to other instructions. The instruction blocks have shapes that facilitate the understanding of where new instructions can be positioned, and make it clear where blocks of programming (e.g., inside a loop) begin and end. *Scratch* is mainly intended for programming two-dimensional animated interactive media, including games.

In 2013, Dasgupta presented an addition to the *Scratch* programming environment that enables programmers to use online data. This addition allows programmers to develop games such that gamers can return to the part of the game where they left off, applications where users can save what they create and retrieve it later, and so forth. These online variables may also be shared, for example enabling the implementation of chat clients (Dasgupta, 2013). In subsequent research, Dasgupta and Mako Hill extended this research to provide data science tools through *Scratch* that enable data access, analysis, and visualization (Dasgupta & Hill, 2017).

Flannery et al. discussed the design of *ScratchJr,* a version of the *Scratch* programming language designed specifically for 5- to 7-year-old children. They identified the main challenges for this age group as the heavy reliance of programming languages on text, developing motor skills that may get in the way of manipulating visual programming elements, and cognitive skills that are still developing. *ScratchJr* relies on icons instead of text, uses large icons to address motor issues, and shows few available instructions at a time to address cognitive limitations (Flannery et al., 2013).

Tutorials are also important to get children started in a programming environment and to learn advanced skills. Harms et al. presented a way to enhance programming skills for middle-school-aged children (typically 12- to 14-years-old) through automatically generated tutorials. The system, implemented for the *Looking Glass* programming environment, which is part of the *Alice* family of programming environments, generates step-by-step tutorials from working code-snippets uploaded to an online repository. For example, if children see an animation they like in a code snippet, they can get a tutorial that tells them how to apply it to characters in their own programs. In a study with 10- to 16-year-old children, the researchers found that tutorials enabled children to complete programming tasks more effectively than a controlled condition without tutorials (Harms et al., 2013).

Another way to obtain tips and feedback is through online communities. A study of a *Scratch* online community found children provided motivational feedback, personalized tutoring, and sought help, among other activities (Fields et al., 2015).

Even though block-based visual programming has become standard for teaching programming to elementary-aged children, it is also being increasingly used in introductory programming courses for teenage students. However, no such language is used in core computer science courses in college or in the software development industry. When teenagers are exposed to both types of programming, there is evidence that they appreciate the ease of use of block-based visual programming, but see text-based programming as more powerful (Weintrop & Wilensky, 2015). To address the transition from block-based visual programming to text-based programing, some researchers have begun studying hybrid programming environments (Weintrop & Wilensky, 2017).

Other researchers have focused on how children learn to program using block-based visual languages. For example, Hansen et al. studied the user-centered concepts used by children when creating digital stories with one of these languages and found these develop between the pre-teen years and teenage years (Hansen et al., 2016). Others have proposed the use of detailed analysis of individual students' development to better understand how they grow in their engagement with programming (Pantic et al., 2016).

There are also environments that can teach programming concepts, but within a narrow context. Tarkan et al. (2010) developed a cooking-based programming environment for children. The environment enabled children to program recipes by using a *Nintendo Wiimote* and *Nunchuk* to control a virtual chef who would prepare virtual dishes (Tarkan et al., 2010).

Software development also involves activities that lead to programming, such as design idea generation. Katterfeldt and Schelhowe conducted 40 workshops with 9- to 14-year-old children to develop a modeling tool to help children design items of interest. The tool enabled children to move from a storyboard to a more structured storygram to a program diagram (Katterfeldt & Schelhowe, 2008).

Game and simulation builders share elements with programming tools and tend to follow visual user interfaces. Examples of these tools include *AgentSheets* (Repenning et al., 2000), *Kodu* (MacLaurin, 2009), and *BlockStudio* (Banerjee et al., 2016). Also incorporating gaming elements were *ToonTalk* (Kahn, 1996), which enabled children to learn to program while playing a game, and *Magic Words*, where children could make simple games by adding instructions on top of images (Kindborg & Sökjer, 2007). Other platforms present programming challenges in game-like formats, such as *Code Baymax*, *Kodable, Lego Bits and Bricks, Lightbot,* and *The Foos* (Simões Gomes et al., 2018). In addition, there have been explorations of children designing their own mixed-reality games (Litts et al., 2019).

Another way to motivate children to program is to use programming to control physical devices, such as the *BBC micro:bit* (Cabrera et al., 2017; Knowles et al., 2019), robots, or smart home devices (Seraj et al., 2019).

An obvious challenge with visual programming is that it relies on children's vision, posing a barrier to children with visual impairments (Pires et al., 2020). Milne and Ladner analyzed popular block-based visual programming environments and identified accessibility barriers in accessing output, accessing programming elements, moving blocks, understanding a program's structure, and knowing the type of block needed in a particular location of the program. They designed a prototype system, *Blocks4All*, that addresses these barriers (L. R. Milne, 2017; L. R. Milne & Ladner, 2018). Pires et al. conducted a similar survey of visual block-based programming environments and found evidence supporting the use of robot-based programming to support activities by children with different levels of visual abilities (Pires et al., 2020).

Tangible programming

Another way to make programming more accessible and to avoid problems with text programming is to program with tangibles. Such environments often involve physical blocks or bricks that are put together to represent programs.

The MIT Media Lab conducted some pioneering work in this area, including tangible programming bricks (McNerney, 2004), *FlowBlocks,* and *SystemBlocks* (Zuckerman et al., 2005). These were construction kits that enabled children to create simulations of generic structures. The rationale behind these manipulatives was to provide children with the ability to interact with dynamic behavior at the symbolic level.

Conducting similar work, Wyeth and Purchase's electronic blocks included sensors, actuators, and logic blocks that could be put together to create simple programs that could act as part of play artifacts children created, such as vehicles and robots. The blocks were designed for 4- and 5-year-old children (Wyeth & Purchase, 2003).

One of the more active researchers in the area of tangible programming has been Mike Horn. Most of his research on tangible programming has been conducted for use in museum exhibits. In 2007, Horn and Jacob presented the *Quetzal* language, which used tangible parts that children could use to put together programs. The parts did not have any electronics; instead, they were scanned in order for a computer to compile and run the code (Horn & Jacob, 2007). The work continued with a tangible computer programming exhibit for the Boston Museum of Science (Horn et al., 2008). The system consisted of wooden blocks with labels that could be joined together to create a program to control a robot. To make this system work best in a museum setting, it followed five design considerations for an inviting exhibit: easy to learn, engaging, supportive of group interaction, inexpensive, and reliable. An evaluation of the exhibit compared it to a graphical user interface. The evaluation found that both the graphical and tangible exhibit were easy to understand, but visitors were more likely to try the tangible exhibit. They also found that involving multiple participants led to longer engagement with the exhibits, and that children were more active under the tangible condition (Horn et al., 2009). Later on, Horn et al. (2013) moved this programming concept to interactive books designed for preschool and early elementary school children. The interactive books enabled children to use stickers to program actions of the book's main character on a smartphone or tablet (Horn et al., 2013).

Another line of research in museums includes work on *TuneTable*, which enables visitors to explore basic computing concepts such as loops and conditionals in the context of making music. The user interface consists of blocks that need to be placed and connected on an interactive tabletop, representing sounds or programming control structures (Long et al., 2020).

Another line of tangible programming research was with *Tangicons*. Scharf et al. first presented *Tangicons*, physical cubes designed for kindergarten children to learn basic programming concepts. Similar to the blocks designed by Mike Horn, these cubes did not have any electronics in them but instead were recognized through vision technology. To evaluate them, the researchers set up a simple game that involved programming a set of LED lights. To win the game, the children had to understand how to produce light sequences with the cubes. The researchers found that the children seemed to enjoy the game and were able to successfully use the cubes (Scharf et al., 2008). A few years later, Scharf et al. discussed the evolution of *Tangicons*, with its latest version implemented using *Sifteo* cubes and a larger display for output that also included sound. The objective of the game activity was for the children to move an avatar along a road to a desired location. A group of four players had to work together and negotiate how to set up instructions through the cubes to get the avatar to its desired destination. The game included multiple levels with increasing difficulty that required more complex decisions (Scharf et al., 2012).

Programming with tangibles can also be useful for children with vision impairments. A group at Microsoft Research, for example, developed *Torino*, which enables children to program by physically connecting “instruction beads.” The beads could be used to play , pause, or loop sounds (Morrison et al., 2020; Thieme et al., 2017).

Sometimes teaching programming does not even have to involve computers. For example, the *Haathi Mera Saathi* game concept uses cards to teach programming concepts to children who do not have access to computers (Unnikrishnan et al., 2016). Similarly, when teaching children to program a *Bee-Bot* (only programmable through physical buttons), another group of researchers scaffolded the programming activities by enabling children to write their program ahead of time using cards or pencil and paper (Angeli & Valanides, 2020). A more elaborate yet similar approach, *CTArcade*, involved 10- to15-year-old children moving from solving puzzles, to using game boards, and eventually to using computers to develop algorithms (T. Y. Lee et al., 2014).

In a similar effort, Wang et al. presented *T-Maze,* a tangible programming tool designed for 5- to 9-year-old children that used wooden blocks that could be identified through computer vision. In the system, children had to program a set of instructions to go through a maze. They could see the maze and their current location in it by looking at a computer display (D. Wang et al., 2011).

Other work on tangible programming includes the research by Weller et al., who developed a tangible state machine built with a computationally enhanced construction kit. Using this state machine, children could create algorithms specifying the behavior of an avatar and its enemies in a game (Weller et al., 2008).

Any programmer knows that an important task in programming is debugging, but how does one debug a tangible program? Sipitakiat and Nusen worked on addressing this problem. They embedded debugging abilities in the tangible programming system itself by allowing children to execute the program one block at a time. In a study with fifty-two 8- and 9-year-old children, the researchers found that the children were better able to analyze problems in their programming when the debugging capabilities were available (Sipitakiat & Nusen, 2012).

There has also been research on programming by example through the use of motion. An early case comes from Frei at al., who developed *curlybot*, a palm-sized robot shaped approximately like half a sphere with wheels at the bottom. Children could move *curlybot* on the floor, record its motion, and then ask *curlybot* to repeat the motion once or in a loop if desired (Frei et al., 2000).

A longer line of research comes from Raffle et al. (2004), who developed *Topobo*, a construction kit with kinematic memory. With *Topobo*, children could put together skeletal-type structures that could then be physically transformed, and then these transformations replayed. Eighth grade children were able to develop moving structures using *Topobo* (H. S. Raffle et al., 2004). In follow-up work, Raffle et al. added components that enabled the control of behavior through tangible devices and modified game controllers that extended *Topobo's* "record and play" functionality to enable recording, sampling, sequencing, and performing (H. Raffle et al., 2006; H. Raffle, Ishii, et al., 2007).

Programming for children has also been taken to larger environments. Montemayor et al. studied the physical programming of interactive rooms by 4- to 6-year-old children. They found children had difficulty distinguishing programming from participating in the programmed environment, but were able to make simple programming constructs (Montemayor et al., 2002). Mattila and Vaatanen developed prototypes for programmable interactive playground environments where children could create and play games. Indoor playgrounds provided children with inputs through a floor set up with sensors that gave audio and video feedback. Children could program the environment using a visual tool (Mattila & Väätänen, 2006). Fernaeus and Tholander studied the design of innovative interactions to enable groups of children to collaboratively program in a room environment. They highlighted the social and physical aspects of the activity. Rather than having a tight coupling between physical and digital elements, they moved all tools to the physical domain, and showed the results of actions in the digital domain. They found their setup enabled groups of children to program together, with most of the collaboration occurring without the use of technology (Fernaeus & Tholander, 2006a, 2006b; Tholander & Fernaues, 2006).

Learning about machine learning

The growth in societal interest in artificial intelligence has trickled down to research on teaching children about the topic. One group working on this topic, led by Oren Zuckerman, developed *Scratch Nodes ML*, which enables children to create gesture recognizers using *Scratch* (Agassi et al., 2019). The same group studied how children can understand machine learning concepts by experimenting with training and evaluating a gesture recognizer (Hitron et al., 2019). Another researcher focused on teaching children about machine learning through gestures is Zimmermann-Niefeld, who appealed to 14- to 17-year-old children through sports, helping them build recognizers for athletic moves (Zimmermann-Niefield et al., 2019) and later using the same technique to use the recognizers to control sprites (i.e., animated images) in *Scratch* programs (Zimmermann-Niefield et al., 2020).

Evaluating and understanding activities

As programming activities are making their return to schools, researchers are looking for novel ways of understanding and evaluating children's programming activities and abilities. For example, researchers used the *Computational Thinking Test* to successfully predict student performance in a *Code.org* course for 12- to 14-year-old children (Román-González et al., 2018). Others have worked on automated tools to evaluate computational thinking concepts displayed in children's programs, with an example being the work on *Dr. Scratch* (Troiano et al., 2019). Hansen et al. proposed a rubric for analyzing user-centered design components in children's programs and found that 10- to 12-year-old children are more likely to use them than 9- to 10-year-old children (Hansen et al., 2016).

Other work aims at understanding how children program and how they differ from each other during programming activities. For example, Papavlasopoulou et al. used eye-tracking to study differences between 8- to 12- and 13- to 17-year-old children during programming activities, finding that younger children spent more time looking at the appearance of the characters they used in the programming environment while the teenagers were more likely to focus on programming tasks (Papavlasopoulou et al., 2017). In addition, they found that children's gaze patterns were highly-correlated with their attitudes (e.g., excitement, intention) about programming (Papavlasopoulou et al., 2018). The same group studied facial expressions during collaborative programming activities by 13- to 16-year-old children, finding they could predict the quality of the participants' collaborative experience, which they measured through surveys (K. Sharma et al., 2019). In a similar vein, Almjally et al. studied 6- to 7-year-old children's body gestures during programing activities in both visual and tangible environments. They found that children who used more gestures during programming activities learned more programming concepts during the recorded activity than children who used less gestures (Almjally et al., 2020).

Thinking about digital toolkits, Iivari et al. identified various roles (i.e., designer, pupil, clown, inventor, leader, and builder) children can take in these activities and concluded that it takes time for children to develop a designer role (Iivari et al., 2018).

High-level principles

Given the significant amount of research in this area, some researchers have taken a wider view, and offered high-level advice, principles, and thoughts based on their experiences with children's programming environments.

Based on his experiences with text-based environments, Sheehan developed recommendations for the development of programming environments for children based on 6- to 10-year-old children's understanding of computer programming. He recommended making the use of multimedia resources an integrated part of the programming environment, providing high-level instructions to match children's interests, providing an easy way to move from seeing programs running to showing their mechanics, and letting children easily run programs when they are not interested in programming (Sheehan, 2003).

Reflecting on experiences with construction kits for kids, Resnick and Silverman recommended the following guiding principles: support authoring, support novices, provide a wide range of exploratory activities, provide opportunities to encounter powerful ideas, support many ways of getting things done, favor simplicity, make basic instructions map to concepts that matter, enable children to get a lot done with little programming, invent things that you would want to use yourself, and iterate development (Resnick & Silverman, 2005). This team was working on releasing *Scratch* at the time and had previously researched computationally augmented bricks, beads, and badges (Resnick et al., 1998).

Blikstein contributed a survey of constructionist toolkits arising from the pioneering work of Seymour Papert and others at the MIT Media Lab. The survey discussed these technologies largely from an MIT Media Lab perspective, including a discussion of *LEGO/Logo* (which later evolved into *LEGO Mindstorms*), programmable bricks, the *Cricket* platform (a predecessor to *Arduino* and *Raspberry Pi*), *Topobo*, *RoBlocks*, and the *LilyPad Arduino* (Blikstein, 2013).

To better enable children to program and express creativity, Mike Eisenberg and colleagues argued for a change in the approach to children's programming. They advocated making programming a more informal, approachable, and natural activity compared to the traditional approach of writing programs to show something on a display or to control a robot. Examples provided by the authors included the use of computer-augmented paper components to create art, programming robots by laying readable pieces of paper on the floor, and programming large public surfaces (e.g., a planetarium sphere) (Eisenberg et al., 2009).

A larger question is what type of activities to conduct with children given all the options that are available. Some researchers have begun to answer this question considering how programs are entered and how output is produced, whether visual or tangible. In a study with 7- to 10-year-old children, Zhu et al. found that visual input for programming helped children focus more on problem solving than tangible input, but tangible input could lead to better class discussions. Similarly, tangible output promoted more causal reasoning and class engagement than visual output, but visual output made it easier for children to spot similarities across problems (Zhu et al., 2016).

Digital making

Another step in making programming more concrete is to program tangible items. One way of doing it is to enable children to design physical artifacts. Another is to add computing elements (including sensors and actuators) to clothes, textiles, and crafts.

Creating physical artifacts

The advent of affordable three-dimensional printers has brought about a downpour of activity in the *maker movement*, where researchers, practitioners, and hobbyists design novel physical artifacts. The child-computer interaction community, and in particular Mike Eisenberg, foresaw the maker movement and began research in this area long before most people heard about three-dimensional printers.

More specifically, Eisenberg designed several systems that allowed children to design and build physical artifacts (Eisenberg et al., 2003). These have included artifacts made of folded paper, three-dimensional objects visualized through transparencies, mathematical surfaces modeled by slices of wood, and gears made out of wood (Eisenberg & Eisenberg, 1998). Eisenberg also proposed the use of a variety of novel materials in technologies for children, including materials that change color based on temperature, shape-memory alloys that return to a given form, and piezoelectric materials that can produce electricity if someone applies force to them (e.g., pressing) (Eisenberg, 2004).

As three-dimensional printers became more affordable, Leduc-Mills and Eisenberg developed *UCube,* an input device to help children with three-dimensional design activities. The researchers noted a common difficulty in three-dimensional design with managing rotations and perspective on a two-dimensional screen. *UCube* provided a tangible user interface that could be used to design simple three-dimensional objects, such as prisms (Leduc-Mills & Eisenberg, 2011).

Later, Eisenberg discussed the challenges associated with the growth of three-dimensional printing in order to leverage it for children's education. These included expanding the range of physical media that can be printed (i.e., going beyond ABS plastic), enabling three-dimensional output composed of many discrete pieces, making three-dimensional printing portable and ubiquitous, adding tools for post-printing jobs (e.g., finishing, decorating), and developing child-friendly three-dimensional design and modeling software (Eisenberg, 2013).

Also, with the goal of children designing three-dimensional shapes, Follmer and Ishii presented *kidCAD*, a digital clay system. Their system enabled children to create three-dimensional models of existing objects (e.g., toys) and modify or mix them with other objects (Follmer & Ishii, 2012). With a similar goal, Yung et al. developed *Printy3D*, which used tangible interaction and augmented reality to support three-dimensional design (Yung et al., 2018). Oriented toward building prototypes, Kang et al. presented *PrototypAR*, which also used augmented reality, but in this case with the focus on enabling children to build prototypes of physical artifacts using paper materials (Kang et al., 2019).

Sometimes the challenge is helping children build items from existing physical components. Tseng et al. added the ability to record and document children's actions in a system that enabled elementary school children to put together tangible machine components. Having access to successful examples developed by other children had a positive impact on the children's use of design strategies and their learning outcomes. Provided examples helped both in situations where children could no longer make progress on their own and by providing inspiration for new strategies. Children were also able to review their previous work, which helped them reflect on what they previously accomplished (Tseng et al., 2011).

Digital toolkits

A related line of research goes beyond the design of physical artifacts by adding computing to these artifacts. Maker spaces and digital fabrication labs (i.e., FabLabs) have become increasingly popular and are often seen as an approachable way of teaching computational thinking, programming, and digital literacy that appeals to a wide range of children (T. Bekker et al., 2015; R. Johnson et al., 2016). There are even experiences with national-level initiatives (Eriksson et al., 2018). Researchers have called for activities with these toolkits to include reflection and an awareness of the design process (T. Bekker et al., 2015; R. C. Smith et al., 2015), be inclusive of underrepresented groups (Holbert, 2016a, 2016b; McBeath et al., 2017), social (Meintjes & Schelhowe, 2016), as well as help children build self-efficacy, motivation, creativity, interest, ownership of creations, and the ability to grasp concepts in the activities (Angello et al., 2016; Chu et al., 2015; Katterfeldt et al., 2015). While most activities involve only children and facilitators, there are also experiences that try to bring together families in digital fabrication activities (S. T. Jones et al., 2019; S. H. Kim & Zimmerman, 2019).

The types of materials that can be involved in digital toolkits is quite varied. For example, Berglin began experimenting with smart textiles in the construction of interactive toys. She used textiles that transformed thermal information, pressure, and optical information into electrical signals as sensors. She also used shape memory materials and chromic materials as actuators (Berglin, 2005).

One of the most influential projects in this area came from Leah Buechley. She first explored the use of electronics combined with textiles and contributed a taxonomy of the types of activities children may engage in during such projects including hardware-, textile-, and software-related activities (Buechley et al., 2006). Her work eventually gave rise to the development of the *LilyPad Arduino*, which has been widely used in workshops, in particular with girls. For example, Kuznetsov et al. presented a set of strategies for mentoring children aged 10 to 12 through textile computing workshops. The researchers developed the strategies based on five weekly workshops with low-income girls using the

LilyPad Arduino. The strategies included enabling participants to independently fix or troubleshoot projects, to use the workshops as art therapy and as a way to break boundaries by bringing participants to a different physical context, to partner with volunteers, and to experience creative freedom (Kuznetsov et al., 2011). Continuing this line of work, Qiu et al. presented a curriculum for teaching programming through the use of computational textiles. The activities were based on the *LilyPad Arduino*, including the addition of the *ProtoSnap* board, which provided pre-made circuits connected to the *LilyPad Arduino* microcontroller board, enabling students to focus on the programming instead of worrying about designing the circuits. They also included the *ModKit* visual programming environment, which shared similarities with the visual look of *Scratch.* The researchers evaluated the curriculum through three workshops held in 2011 and 2012. The participants were teenagers, a majority of them girls. Questionnaires suggested that the participants became much more comfortable with programming computers and building electronics after participating in the workshops (Qiu et al., 2013).

In similar research, Katterfeldt et al. presented their work on the *EduWear* project, which investigated the use of smart textiles. They developed a construction kit for smart textiles and conducted workshops with children to evaluate it. The kit consisted of a microcontroller board, sensors, actuators, and connectors. To program the textiles, children used a visual programming language called *Amici*. Participating in the workshops helped children become more self-confident with technology and enabled them to be more curious about technology in their daily lives (Katterfeldt et al., 2009).

Another designer of wearable computing, Ngai et al. presented *i*CATch*, a wearable computing framework intended for children and novices to program their own wearable computer setups. The system included a set of plug-and-play components and a visual-textual programming environment (Ngai et al., 2010). In a similar effort, focusing on 5- to 12-year-old children, Kazemitabaar et al. presented *MakerWear*, which enabled children to put together interactive wearables through tangible, plug-and-play components (Kazemitabaar et al., 2017).

Other researchers have focused on children making other types of artifacts. For example, Kafai and Vasudevan presented workshop ideas for children creating augmented board games (Y. Kafai & Vasudevan, 2015). Yoon et al. created *HandiMate*, a program that enabled children to create robots from basic craft materials (Yoon et al., 2015). Sheriff et al. presented *CataKit*, a construction kit for children to make mechanical contraptions inspired by Rube-Goldberg machines (Sheriff et al., 2017). Bar-El and Worsley focused on building musical instruments with electronics (Bar-El & Worsley, 2019).

Some projects that are a bit closer to electrical engineering than programming need to make use of breadboards to connect electronic modules. DesPortes et al. presented *BitBlox*, an alternative to traditional breadboards that purposefully makes visible the connections within modules (DesPortes et al., 2016).

Storytelling

Supporting storytelling has also been a popular theme in child-computer interaction. Storytelling has played an important role in human history as a way of transferring and retaining information, with oral traditions being an example. In fact, it is easier to remember sets of facts if they are put together in a story than if they are in a list (Bower & Clark, 1969). One could even argue that stories were the first databases. Storytelling can also help children develop communication skills, express themselves, and imagine themselves as someone they would like to be. Interactive technologies can play a positive role in storytelling by allowing for storage and the ability to copy, share, and edit stories. They can also provide the means to create nontraditional forms, such as nonlinear stories.

Programming and storytelling

Programming can enable children to express themselves more fully than through traditional oral or written means. At the same time, being able to tell a story through programming can make programming more enticing for some children.

An example of the former comes from a study by Vincent who found that 10- and 11-year-old visual learners who normally had difficulty expressing themselves through writing improved the volume and complexity of their writing when combining it with visual displays programmed in *MicroWorlds* (Vincent, 2002). Another group that may benefit from storytelling is imprisoned youth. Ruggiero and Green worked with imprisoned teenagers (14 to 16 years old) in a workshop where the children designed and created narrative games using *Twine*, a tool for creating interactive, nonlinear stories that can include the use of variables and conditional logic (Ruggiero & Green, 2016).

An example of the latter comes from Kelleher et al. who recognized the potential of storytelling for motivating girls in middle school (generally 12 to 14 years old) to program. They developed a version of the *Alice* programming environment with additional scaffolds to facilitate storytelling, such as pre-programmed animations of social interactions, story starters, and a tutorial with story examples to get girls started. In their study, girls using the storytelling version of *Alice* spent much more time programming than girls using the standard version of *Alice* (Kelleher et al., 2007). An example with younger children came from Baranauskas and Posada, who designed a system for children 4 years of age and older that, based on storytelling activities, enabled children to collaborate in creating content, and included some basic computational constructs to enable execution of a sequence of commands (Baranauskas & Posada, 2017).

Games with strong stories can factor into both sides of the equation: they can enable children to tell stories in unprecedented ways and can motivate children to program. Robertson and Good took advantage of this opportunity and conducted activities with children between the ages of 12 and 15 who built games using the *Neverwinter Nights* toolset (J. Robertson & Good, 2005). They were highly motivated by being able to design their own characters and put together plots. In earlier work, these researchers had studied the creation of virtual environments using game engines for children to participate in stories as characters (J. Robertson & Good, 2003). Robertson and Nicholson continued this line of research by studying the scaffolding children need to develop their own adventure games (J. Robertson & Nicholson, 2007).

Multimedia storytelling

Multimedia applications provide children with novel ways of putting together stories. Research in this area has included the production of stories based on character manipulation, various forms of collaborative storytelling (both face-to-face and remote), storytelling with mobile devices that can capture relevant content, emphasizing specific aspects of storytelling (e.g., emotional expression), and enabling storytelling in specific contexts. The following paragraphs include examples of each of these research aims.

An example of an application that enabled children to manipulate story characters was *Graphic StoryWriter*. It automatically generated written stories based on children's manipulation of the characters and props in the software (Steiner & Moher, 2002). Following a similar idea, but with the added functionality to collaborate in storytelling, Machado et al. developed *Teatrix*. Children could use *Teatrix* to collaboratively tell stories and participate in drama performances in a virtual environment (Machado et al., 2000).

The theme of collaborative storytelling is present in many other applications. An early example of online collaborations comes from Ellis and Bruckman, who developed a system to support sixth grade children creating stories based on oral histories from elders (Ellis & Bruckman, 2001). Other environments combined both face-to-face and remote collaboration, such as *FaTe2* (Garzotto & Forfori, 2006). Similarly, Di Blas and Boretti described the use of a multimedia storytelling tool with 5-year-old children. The teachers helped by selecting the topics and the overall narrative. The children participated by selecting pictures related to the topics and recording voice comments about the pictures. Through the activity, children learned to be concise, relevant, and clear (Di Blas & Boretti, 2009). Later, Di Blas et al. discussed wider experiences with the same tool, including a survey of 153 teachers who used it. The biggest gains, according to the teachers, were in terms of engagement and interest in the subjects of the stories children participated in telling (Di Blas et al., 2012). *Fiabot!* was another example of a multimedia storytelling tool with a structured approach. It enabled elementary school children to create stories based on templates. The templates were set up for different types of stories that guided children in creating characters, setting up a plot, and incorporating other necessary story elements (Rubegni & Landoni, 2014). In follow-up work, Rubegni et al. identified methods to detect gender stereotypes in children's stories with the goal of attenuating such stereotypes (Rubegni et al., 2019).

KidPad was an example of a less-structured application for storytelling that supported face-to-face collaboration through multiple mice connected to the same computer. *KidPad* enabled children to create visual stories in a large zoomable space where they could draw, type, and create hyperlinks across the space (Benford et al., 2000; Druin et al., 1997; Hourcade, Bederson, & Druin, 2004b; Stewart et al., 1999). Stanton et al. (2001) augmented *KidPad* to function in a room environment with tangible controls (Stanton et al., 2001). It inspired more recent work supporting collaborative storytelling using tablets (Hourcade, Bullock-Rest, et al., 2012).

Beginning in 2010, storytelling applications have supported mobile storytelling. *Mobile Stories*, for example, was an app children could use to tell stories by incorporating pictures and text they generated with a handheld device (Fails et al., 2010). This effort was followed by *StoryKit*, which took many of the lessons learned with *Mobile Stories*, and became widely used after being shared through Apple's App Store (Bonsignore et al., 2013).

For teenagers, social media is a common outlet for storytelling and expression. McRoberts and colleagues studied teenagers' use of social media related to video creation. First, they studied how teenage authors on *YouTube* differed from adult and professional authors, finding that while they followed similar audience engagement practices, the teenagers typically lagged behind in video editing and meta-content skills (McRoberts et al., 2016). McRoberts et al. later conducted a long series of workshops to better understand video creation, finding interest in specific kinds of videos (e.g., skits, goofing around, documenting experiences) and the importance of social aspects to video creation (McRoberts et al., 2019).

In other recent and similar work, Pittarello and Bertani presented *CASTOR*, a tablet-based system to support storytelling. *CASTOR* enabled children to choose different types of stories to author (e.g., sequential vs. branching), and specific stages of the story. It then allowed children to tell stories by taking pictures, recording audio, setting a context, and selecting characters (Pittarello & Bertani, 2012). An older example designed for a specific location comes from Halloran et al., who used handheld devices to digitally augment a field trip for fifth graders, with the goal of providing structure and activities that would lead to creative writing inspired by the trip (Halloran et al., 2006). Rutta et al. presented the use of *Communics*, a tool that enables children to create stories based on comics that can be created individually or collaboratively in an elementary school classroom to reflect on conflicts that may arise in class. They found that children's stories were more complex when collaborating and that children preferred to tell stories together (Rutta et al., 2020).

There are also tools designed only for the capturing of elements that can then be used in stories. For example, Näsänen et al. developed and evaluated a tool for sharing what happens in a kindergarten classroom. The mobile app enabled teachers and children to share pictures and video with parents during the school day. Mostly teachers used the app, but children also shared pictures and video. There was a novelty effect, as the app was used much more frequently in the first half of the deployment compared to the second half (Näsänen et al., 2009). Earlier, Mäkelä et al. put together a similar system for use by 8- to 15-year-old children (Mäkelä et al., 2000).

Some applications make an emphasis on specific aspects of stories. For example, Ryokai et al. designed *StoryFaces*, a storytelling tool that put an emphasis on the role of emotional expressions. *StoryFaces* enabled children to record their emotional reactions to a narrative and incorporate them as part of the story. More advanced features enabled children to rearrange stories or create them from scratch. Through work with 4- to 10-year-old children, the authors found that *StoryFaces* helped children engage with stories and think about the role of emotion in stories (Ryokai et al., 2012).

Other researchers have focused on enabling storytelling in specific contexts. For example, Wood et al. presented a mobile app called *The Department of Hidden Stories*. It was designed for use in libraries and prompted children to write stories that involved elements from books they checked out. The children wrote stories inspired by the books on paper. The app also suggested changing the fortune of the main character in the story by rolling virtual dice and encouraged children to continue the story by gaining inspiration from other books (G. Wood et al., 2014).

Another effort on telling stories in specific contexts came from Axelrod and Kahn, who explored the use of data visualization tools to support parents interacting with children in constructing family narratives based on migration stories. The visualization tools enabled families to interpret family stories within broader socioeconomic and historical contexts (Axelrod & Kahn, 2019).

Moving further into the personal domain, Gray et al. designed *Trove*, a system to enable children who do not live with their birth families to hold on to memories and precious objects. They found that multimedia storytelling could help children construct identity narratives (S. Gray et al., 2020).

Physical and tangible storytelling

Making storytelling more concrete may help many children connect with storytelling more readily. In particular, in traditional play, children often tell stories with dolls, action figures, and other toys at their disposition. Some research projects have taken advantage of these physical aspects of storytelling. These projects have included the use of tangible characters, robots, room-sized storytelling environments, environments that support physical and digital story elements, and the use of physical devices designed to enable new forms of storytelling.

An example using tangible characters was *ShadowStory*, which bridged very traditional forms of storytelling in traditional Chinese shadow puppetry with digital forms (F. Lu et al., 2011). The system's setup enabled children to create puppets through pen and tablet input, while handheld orientation sensors were used during performances to control the puppets on a screen. The researchers conducted a field trial with children between the ages of 7 and 9, obtaining positive feedback from the children.

More common forms of toy and character manipulation use embedded sensors. For example, Johnson et al. embedded sensors in a plush toy. Manipulating the toy in turn controlled a virtual character on the screen. The idea behind this work was to have the input device mirror the item that it acts upon, appearing inviting and friendly and producing different results given different contexts (M. P. Johnson et al., 1999). Also using plush toys, Paiva et al. studied how children may express emotions by using a doll with sensors (Paiva et al., 2002). Along similar lines, Marco et al. presented a storytelling game designed for children aged 3 to 4 years old. The game involved a tabletop setup and a vertical display where children could use tangible toys to create stories in a farm environment. Putting the toys on the tabletop would cause their virtual versions to appear on the vertical display, which provided the ambience of a farm. Joining the toys with other physical elements led to actions such as a hen laying eggs (Marco et al., 2009).

Other systems have combined an awareness of children's interactions with tangible characters with other storytelling supports. Examples were Justine Cassell's projects *StoryMat* and *Sam the CastleMate* (Cassell, 2004). *StoryMat* recorded children's stories involving stuffed animals and replayed them to other children (Cassell & Ryokai, 2001). *Sam* was a conversational agent with whom children could tell stories and who was aware of children's interactions with physical items (Ryokai et al., 2003). Sun et al. explored similar ideas for children telling stories with the support of a robot (Sun et al., 2017).

Noncharacter physical items can also be used to tell stories. For example, the *PETS* project enabled children to put together their own robot they could then program to tell stories (Druin et al., 1999). The *Pogo* project used specialized hardware to support collaborative storytelling activities by elementary school children (Decortis et al., 2003; Fusai et al., 2003). *Pogo* emphasized the use of tangible elements for storytelling, the active and physical participation of children, and a bridging of elements from the physical and digital worlds. For example, the camera feature enabled children to capture items from the physical world that would then appear in the digital world. Children could also associate digital elements with physical cards to manipulate digital stories through tangible means. In a similar vein, Montemayor et al. developed a room-sized storytelling environment through the use of embedded sensors and actuators. This project had the goal of taking the storytelling that often occurs when children play with cardboard boxes and other physical items and augmenting it with technology (Montemayor et al., 2004). Soleimani et al. presented similar, yet more structured, ideas for a similar age group through *CyberPLAYce*. This system included physical materials that could be embedded with a variety of sensors and actuators, enabling children to program interactive narratives in a physical space (Soleimani et al., 2016)

Other lines of research have focused on designing innovative devices that can aid in storytelling activities. Labrune and Mackay prototyped ideas for *Tangicam*, a mobile device designed for children to capture pictures and video and then use them to put together narratives (Labrune & Mackay, 2005). They then continued this line of research with work on *SketchCam* (Labrune & Mackay, 2007). Ryokai et al. developed *I/O Brush*, an augmented paintbrush designed to capture images or video that could then be used in a drawing activity on a special canvas (Ryokai et al., 2004). Raffle et al. developed *Jabberstamp*, which enabled children to embed audio recordings into drawings, collages, and paintings they created on paper (H. Raffle, Vaucelle, et al., 2007).

Performance authoring and support

Performances, such as music, theater, and dance, can also be augmented by computers. Most of the work in this area has involved the use of motion tracking. For example, Cuthbertson et al. developed a media environment that used three-dimensional tracking of objects to provide audio and visual feedback, which they used to design performances with fourth- and fifth-grade children (Cuthbertson et al., 2007).

Antle et al. focused on music, working with 7- to 10-year-old children. In their system, children controlled sound outputs in terms of volume, tempo, and pitch through body movements. In a study with 40 children, the authors found that children learned to use the system more effectively using a version of the system where body movements mapped to sounds when compared to an interface where they did not. The children were also better able to explain how the system worked through their bodies, as opposed to doing it verbally (A. N. Antle et al., 2008). Bakker et al. continued this research through exploring the types of embodied metaphors 7- to 9-year-old children would naturally use to express abstract music concepts. The concepts that children explored in the study were volume, pitch, rhythm, tempo, timbre, harmony, articulation, and tone duration. The study identified the most common metaphors children chose (Bakker et al., 2009).

Also using the body, Halpern et al. developed *MoBoogie,* an application designed to help children manipulate and arrange music. To control music, children could move their smartphones along the three axes to change the melody, bass, and drum tracks (with each axis mapped to one track). Moving the smartphone past a threshold switched the loop played in a particular track to a different, random loop (Halpern et al., 2011).

Using more traditional user interfaces, Akiyama and Oore developed *PlaceAndPlay,* a tool to create and record music, designed for children with no music authoring experience. The system included a graphical user interface where children could select recordings, existing songs, instruments, and sound effects, or record their own sounds (Akiyama & Oore, 2008).

A more recent musical experience for children came from Buhl Jakobsen, Graves Petersen, and collaborators, who conducted a workshop with more than one hundred and fifty 3- to 13-year-old children where the children created their own musical instruments using Lego pieces. The instruments incorporated sensors that would play sounds when activated (Jakobsen et al., 2016; Petersen et al., 2015).

Videogames

Research on videogames within child-computer interaction includes how to design engaging educational games, what kinds of elements children like to experience in games, and whether commercial videogames tend to benefit or harm children.

One area where researchers have seen potential gains from videogames is in the design of educational videogames. Revelle provided advice on how developmental theory insights can inform the design of educational games. Her advice included the use of input techniques, such as touchscreens, tangibles, and whole body movement, that are a better fit for children than those designed for adults. Revelle also recommended the use of hints and clues to provide scaffolding and ensure that the games motivate children in developmentally appropriate ways (G. Revelle, 2013).

A common challenge when designing educational games is how to make them engaging. Sherry presented a model of game engagement that moved from developmental factors (e.g., social, emotional, and cognitive), to game play motivations (e.g., social, emotional, and intellectual), to game genre attributes (e.g., collaborative play, demands, and challenges) (Sherry, 2013). Also looking at engagement, Deater-Deckard et al. proposed a model of engagement states that can be used to take into account individual differences in terms of attention, memory, motor skills, persistence, and positive and negative affect. They argued that such models could be used to help design educational games that work for a greater variety of students (Deater-Deckard et al., 2013).

Investigating the best type of feedback to use in educational games, O’Rourke et al. studied an alternative way of giving feedback and points to children. In a game related to fractions, they compared two reward systems. The first rewarded effort, use of strategy, and incremental progress, while the other, a control, rewarded getting the right answers. In a study with 15,000 children, the authors found that the first approach encouraged more low-performing students to persevere when playing the game (O’Rourke et al., 2014).

On a related note, Celis et al. presented the results of a laddering study to learn about the gameplay preferences of twenty-five 5-year-old children. Among the findings were that the 5-year-olds enjoyed collecting items as rewards in their games and liked some level of challenge required to obtain these rewards (very consistent with the concepts of user experience in Chapter 4). They also preferred interacting with touchscreens over computer mice and enjoyed creating characters as well as experiencing games with humorous effects (Celis et al., 2013).

A very public and high stakes debate on videogames is whether they bring about cognitive benefits to players. Blumberg and Fisch argued that this is such an important question that there should be more resources dedicated to studying children's playing of videogames. They argued that videogames are an integral part of children's lives that can contribute to learning and cognitive development and that developmental psychologists could contribute to better educational videogame design (Blumberg & Fisch, 2013).

In further specifics, Blumberg et al. discussed ways in which videogames may bring about cognitive benefits to children and teenagers and how these could be leveraged in academic tasks. Through a literature review, they argued that skill improvements have been found in areas such as mental rotation, planning, and metacognition (Blumberg et al., 2013). Dye and Bavelier, also supporters of the positive effects of videogames, presented findings on visual attention skills that suggest that children and young adults who play action videogames, on average, score higher than non-gamers in these skills (Dye & Bavelier, 2010).

On the other hand, Boot et al. called into question study results suggesting improved performance in perception and cognition tasks for videogame players. While they acknowledged a strong relationship between gaming experience and cognitive abilities, they also noted methodological shortcomings in the studies that found these relationships (Boot et al., 2011).

In spite of these debates, there is little research on the impact of games that have become widely popular with children, such as *Minecraft*. *Minecraft* uses a successful combination of construction and survival to attract players, allowing children to build their own worlds with unlimited resources (Duncan, 2019).

Play

Play often involves creative activities and has been highlighted as an activity through which children can pretend to be older and try out new roles. There are many different kinds of play but the literature generally points at open-ended, social play as the most beneficial (see Chapter 2).

Play happens in many contexts that may be augmented by technology, for example via adding novel elements to children's play. An example of a novelty is robotic toys, which are likely to become more common in the future. To learn about how children may interact with robotic toys, Fernaeus et al. studied children's interactions with *Pleo* robots over several months. They found that while the participating families expected the robot to work as a toy, they often compared it to a pet. After the initial novelty faded, *Pleo* was treated similarly to non-interactive toys and used as such (Fernaeus et al., 2010). Segura et al. continued researching *Pleo* robots, in this case studying the "migration" of robots from their embodied, physical form to a virtual representation. In a study with ten- to eleven-year-old children, they exposed pairs of children to both physical and virtual forms of the robot, counterbalancing the order in which they were presented. Among the findings, the researchers learned that children did not like it when one of the representations turned off while the other one was on, perceived the physical *Pleo* as being more real than the virtual version, associated the physical *Pleo* being off with it being dead, and could understand the concept of migrations better if they happened more often (Segura et al., 2012).

Also considering robots, Han et al. studied 5- to 6-year-old children's dramatic play enhanced by augmented reality. In their study, half of the children played with a computer-mediated augmented reality environment, while the other half played with a robot-mediated augmented reality environment. The researchers found that children in the robot-mediated condition showed greater interest in play and engagement in the activity as well as with the media used in the activity (Han et al., 2015).

In terms of augmenting existing play practices, one place where this can happen is on tables, where many children enjoy playing with their toys. Interactive tabletop displays bring about this opportunity. Mansor et al., for example, developed *Fantasy Table*, a setup for 3- to 4-year-old children to facilitate fantasy play. It was implemented using a *MERL DiamondTouch*, which can differentiate between users who are touching it, but only allows one input point per person. The setup enabled children to manipulate virtual objects (e.g., characters, furniture) on a virtual scene. A comparison to a similar physical setup uncovered different play patterns, with the tabletop setup leading children to pay less attention to the scene. The study also emphasized the importance of solving low-level usability issues in order to provide engaging experiences (Mansor et al., 2009).

Kammer et al. also worked with kindergarten-aged children in using tabletop displays. They developed games including activities such as path tracking, puzzles, and shape tapping. The games were designed for multiple simultaneous users and children were able to successfully play during an evaluation of the system (Kammer et al., 2014).

Adding technology also has the potential of bringing new opportunities for play in situations where boredom may cause problems, such as long car trips. Hoffman et al. discussed their experience designing and evaluating a game for use during family car travel. The game, called *Mileys*, integrated location-based information, augmented reality, and virtual characters. It sought to engage children with the places through which they were traveling, integrate family members, and encourage safe and environmentally sound driving. An evaluation with six families yielded more information on the goals of children and parents during the trips: while children wanted to be entertained, parents wanted to strengthen family bonds and educate their children (Hoffman et al., 2013).

There are also opportunities for taking traditional game concepts and making them more engaging and interesting. An example was Bonsignore et al.'s research on an adaptation of a scavenger hunt in the form of an alternate reality game, where players collaborated to collectively put together a story distributed in multiple media forms and accessible through different devices (e.g., email, text, telephone). While these games are gaining popularity among adults, the researchers discussed their experiences developing a game for 13- to 15-year-olds. One of their main findings was the usefulness of creating an in-game character with whom players could relate to motivate their play while they played as themselves instead of controlling an avatar. Other recommendations included establishing guidelines for the use of social media for collaboration, making time for group discussions, and providing clues so players know when they should pay critical attention to the information they find (Bonsignore et al., 2013).

A final concern to take into account that is related to play is how children manage boredom and how to turn that boredom into creative play. Begnaud et al. studied this question with a group of 7-to 13-year-old children and found that boredom often arises from doing something for too long or from lack of control over activities and that tangible objects in physical spaces could spark activity ideas and control over activities could help pull children from boredom (Begnaud et al., 2020).

Other examples of games, in particular those involving physical activity, are discussed in Chapter 11 under *Promoting healthy lifestyles.*

Summary

Much of the research in child-computer interaction has focused on the goal of providing children with an unprecedented ability to be creative and modify their environment. Doing so can help children grow together with their environment and develop the ability to express ideas and build artifacts.

This has been the main motivation behind the design of programming environments for children (as opposed to preparing a workforce of information technology specialists). These programming environments have evolved from being mainly text-based (as in *Logo*), to visually oriented languages that require little typing or knowledge of syntax (e.g., *Scratch*), as well as tangible programming systems oriented to young children. In addition, there has been a significant amount of research dedicated to maker spaces and fabrication labs, providing children with experiences in programming and designing wearables, textiles, and crafts with computing components. Related to these endeavors are tools to help design three-dimensional items.

Storytelling is another way to help children express themselves and develop social and communication skills. Research in this area includes programming environments tailored to storytelling, various multimedia storytelling tools, and tangible systems that enable manipulation of physical artifacts to tell stories.

Other creative endeavors supported by computers include tools to author and support music and other performances. These include both graphical user interfaces and whole body interactive systems.

Children's play may involve creativity as well. Most of the research in this area is in studying what happens to children when they play videogames and how to design better educational videogames. There are also examples of games designed specifically for families and games that explore the ubiquity of computing, such as alternate reality games.

Together, these efforts provide children with novel ways of expression, new approaches to problem-solving, and playful ways to learn.

Chapter 8
Collaboration and Communication

With editorial feedback from Lana Yarosh, University of Minnesota

Social interactions are at the foundation of healthy child development. The foundation begins with a secure attachment to primary caregivers and continues with the social aspects of learning discussed by Vygotsky and others, including the scaffolding children can receive in order to complete a task with someone else's help (see Chapter 2 for a discussion of these concepts).

Researchers in child-computer interaction, aware of these concepts from developmental psychology, have looked for ways to provide children with computing activities where at the very least communication and collaboration are not hampered, and at best are encouraged and facilitated. The challenge for researchers is to move away from the personal computing paradigm that sees one user per device, with little or no interactions with others.

There are two approaches to facilitating communication and collaboration. One is face-to-face, which focuses on people who are physically nearby. The other has a focus on communicating and collaborating with remotely located people. Another, somewhat unexpected form of interaction that many researchers are studying in the late 2010s, is children's interactions with robots, agents, and voice assistants. The following sections discuss each of these approaches with examples from the research literature.

Face-to-face collaboration

During the 2010s, researchers such as Sherry Turkle sounded the alarm about personal computing devices getting in the way of face-to-face interactions. In her book *Alone Together,* Turkle discusses her worries about family exchanges and other meaningful daily interactions not happening to the extent they used to due to the distracting effect of smartphones and tablets on children's and adults' attention (Turkle, 2017). There is evidence that many parents are aware of these concerns, for example, feeling guilt about using mobile devices while they are with their children in playgrounds (Hiniker, Sobel, Suh, et al., 2015), while others hope that their children can benefit from the use of mobile devices (Papadakis et al., 2019). These attitudes toward children's use of computing devices have been coexisting with children's dramatic increase in their use (Common Sense Media, 2017).

Within child-computer interaction, researchers have long sought to push back against the trend of technology isolating us from those physically near us. This section provides a summary of research on face-to-face collaboration, including augmenting personal computers with multiple devices, moving collaboration to tangible devices, using multitouch tablets, large displays, and hybrid setups.

The early years: multiple mice

Early research on face-to-face collaboration used multiple mice connected to one computer, with children sharing one display. These setups are also known as *single-display-groupware* (Stewart et al., 1999). Part of the motivation for the research dated back to the 1990s and early 2000s when many schools, even in high-income countries, did not have one computer per child. Instead, school children often had to share computers, leading to unequal use.

The evidence from several research studies points at single-display groupware being advantageous for children when compared to setups where children have to share one input device. More specifically the advantages of one input device per child over one shared device include child preference (K. Inkpen et al., 1999), more engaged and active children (K. Inkpen et al., 1999), interactions with other children similar to those observed in paper-based activities (Scott et al., 2003), and better division of labor and work in parallel (Stanton & Neale, 2003). Abnett et al. painted a more nuanced picture through a study with mixed-gender and same-gender pairs of children. They found evidence that girl-girl pairs were just as collaborative and productive in a storytelling task when sharing one mouse as when each controlled their own mouse. The same was not true for mixed-gender and boy-boy pairs, as they displayed more conflict and produced less content when having to share one mouse (Abnett et al., 2001).

There are also multiple ways in which collaboration can work in single-display-groupware. Druin et al., for example, explored one condition called *confirmation collaboration* where both children had to agree on where to navigate, while in the other condition, *independent collaboration*, navigation occurred as soon as either of the children decided to navigate. In a study with pairs of 7-year-old children, confirmation collaboration led to shared goals, less conversation, more concentration on the user interface, and better regard for the tasks. Independent collaboration led to individual goals, more conversation, more concentration on content, and less regard for tasks (Druin et al., 2003).

Singh Pawar et al. (2007) scaled up the study of confirmation versus independent collaboration with groups of five children using educational software. They compared these two collaboration modes with a one-computer-per-child setup. Pre- and post-tests of learning outcomes showed that children in the confirmation mode did as well as children who did not have to share a computer. Boys in particular were affected negatively by the conditions where they had to share a mouse and where there was no confirmation of how to navigate, while the mode of sharing did not affect girls' performance (Pawar et al., 2007). This study confirmed the findings of Abnett et al. (Abnett et al., 2001). These studies also show that boys' problems with sharing cut across cultures as Pawar et al.'s study was conducted in India and Abnett et al.'s was conducted in England (Abnett et al., 2001).

Pawar et al., preceded by Pal et al., had begun exploring the use of single-display-groupware in low-income regions (Pal et al., 2006; Pawar et al., 2007). Moraveji et al. continued the scaling up of these ideas with *Mischief*, a single-display-groupware system capable of supporting dozens of input devices. The system consisted of one computer, one projector, and one computer mouse for each child in a classroom. The system assigned each child a unique cursor. Children could then participate in full-class interactions with learning applications on the computer, where they tried to answer questions or solve problems together (Moraveji et al., 2008). In an evaluation of *Mischief*, Moraveji et al. studied its use with groups of one to 32 children. They found that performance in tasks was only affected by group size when targets were small and all children had to point at them at the same time (Moraveji et al., 2009).

Tangibles

Tangible user interfaces are a more natural way of bringing children together (A. N. Antle et al., 2009). They mirror the collaboration that occurs with physical objects, such as toys. Another advantage of tangibles is that they may make user interfaces more concrete (Manches & Price, 2011).

One area where there has been extensive use of tangibles, as covered in Chapter 7, is in programming environments. Examples include the use of blocks and cubes (Horn et al., 2008; Horn & Jacob, 2007; Hornof, 2009; McNerney, 2004; Scharf et al., 2008, 2012; D. Wang et al., 2011; Wyeth & Purchase, 2003; Zuckerman et al., 2005), stickers (Horn et al., 2013), and even room- and playground-sized programming environments (Fernaeus & Tholander, 2006a, 2006b; Mattila & Väätänen, 2006; Montemayor et al., 2002). These efforts have enabled collaborative programming, which would likely be a more difficult task using a traditional programming environment.

Tangibles have also been useful in supporting other creative and collaborative endeavors such as storytelling, also covered in Chapter 7. These projects have included the use of puppets (F. Lu et al., 2011), figures and plush animals (M. P. Johnson et al., 1999; Marco et al., 2009; R. Nielsen et al., 2009; Paiva et al., 2002), and physical items associated with digital counterparts (Decortis et al., 2003; Fusai et al., 2003). Tangibles have also been used to explore adventure worlds (Price et al., 2003).

A more recent example was the *STORIES* system by Knøsgaard Christensen and collaborators. The system, intended to bring family members together through technology, involved the use of *LEGO* bricks and minifigures, each of the latter representing a family member, embedded with sensors. Family members could combine the use of the bricks with a tablet app to create story scenes, which could then be put together into a story by the whole family (Christensen et al., 2019).

Tangibles can also talk as they support collaboration. Pantoja et al. described how they considered different types of voice agent design to support 3- to 4-year-old children’s collaborative make-believe play. They found that a tangible agent that children could incorporate directly into their physical play worked better than physical versions that could not be picked up, or screen-only versions (Pantoja et al., 2019a).

Learning simulations are another genre where researchers have used tangibles to enable children to work together. Most of these simulations have dealt with sustainability or environmental issues (A. N. Antle et al., 2011, 2014; Bodén et al., 2013; Zhang et al., 2010).

Tangible interaction ideas have also made it to some commercial toys, which provide hybrid experiences where there is often a physical toy combined with a digital experience. Bleumers et al.

conducted a large survey of parents of children ages 4 to 6 to learn about parental involvement in these hybrid play activities. They found that parents participated in these play activities through five roles: supervision, control (e.g., granting access), care (e.g., setting things up, being an audience), play, and instruction (Bleumers et al., 2015). Also thinking about parental involvement, but considering generic collaborative activities, Sadka et al. presented the design of *Awareness Object*, a tangible device that helped provide parents and children with direct awareness of a parent's perceived role in an activity with their child across a mentor-peer scale. They found the *Awareness Object* helped parents be more mindful of how they engaged with their children (Sadka et al., 2018).

In spite of all the positive examples of the use of tangibles, sometimes conflict arises. Marshall et al. studied what happened when children do not want to collaborate and instead want to fight for or maintain control over physical or digital objects. They conducted their research through prototyping sessions involving either tangible or interactive tabletop setups. They observed children's strategies, which included moving items out of reach of others, blocking access to objects with their bodies, and moving other children away (e.g., pushing them, or pulling their arms away) (Marshall et al., 2009).

Mobile devices

With the proliferation of mobile devices, researchers have also looked at how they may be used for collaboration and communication. Cole and Stanton developed guidelines for the use of handheld devices in collaborative activities. They found sharing small displays was difficult and recommended sharing information only at specific points in an activity. Likewise, they recommended that activities be organized to support both tightly and loosely coupled collaboration (Cole & Stanton, 2003). Thinking of one of these forms of collaboration, Fails et al. enabled children to join multiple devices together to, for example, see a picture on one device and text for the picture in the other, or see a larger picture spanning across two devices when experiencing stories (Fails et al., 2010).

It is also possible to think of collaboration with handhelds as moving digital items between devices. An early example of this approach came from Borovoy et al., who studied the creation of software objects called i-balls, which had to be created on a desktop computer but could then be shared between handhelds (Borovoy et al., 2001).

With larger mobile devices like tablets, it is possible to support multiple children simultaneously using a single device. It is also possible for children to take turns using a device, with the advantage that children waiting for their turn can more easily perceive what the child using the device is doing. Hourcade et al.'s work on a suite of tablet-based apps is an example of this approach. Many of the apps and their related activities involved face-to-face collaboration. Uses included encouraging social interactions for children diagnosed with autism, and facilitating communication between clinicians and children with chronic headaches (Hourcade, Bullock-Rest, et al., 2012; Hourcade et al., 2013).

Another trend is the use of handheld devices to encourage social interactions but without sharing devices. For example, Escobedo et al. used handhelds to provide children diagnosed with autism with ideas on how to interact with other children in a playground (Escobedo et al., 2012). Another example is Avontuur et al.'s work with handheld devices to facilitate children's outdoor play (Avontuur et al., 2014).

As children's books make their way to digital platforms, parents are reading these digital books to children as if they were physical books. However, studies on differences between these two types of media for reading are not consistent in favoring one over the other. Lauricella et al. conducted a study observing parents of 4-year-old children reading from both digital and physical books.

They found that reading across conditions was very similar, with no differences in terms of children's story comprehension, but that parents were more engaged with their children while reading computer storybooks (Lauricella et al., 2014). While Lauricella et al.'s finding would appear to slightly favor electronic formats, a survey conducted by Strouse and Ganea with 555 parents of 1- to 4-year-old children found that children participated in reading physical books more often than electronic books and that parents thought their children enjoyed physical books more and paid more attention to them (Strouse & Ganea, 2017).

Large displays

Large displays, both vertical and horizontal (like a tabletop), can also provide a platform to collaborate. While most large displays now have multitouch technology, some early efforts included displays with single touch capabilities, which are still found in many classrooms. For example, Ovaska et al. provided kindergarteners with an electronic whiteboard to conduct creative activities. In spite of allowing only one child to interact with it at a time, which limited the types of collaborations available, it still enabled groups of children to discuss what was happening and provided for engagement through activities designed to give every child a turn to interact with the whiteboard (Ovaska et al., 2003).

Looking at the differences between single and multitouch technologies, and patterns of use in multitouch tabletops, Jeff Rick and colleagues conducted a series of studies. The first study (Rick et al., 2009) involved 15 groups of children aged 7- to 9-years-old. The researchers asked the children to complete a task that involved setting up a classroom, including manipulating tables and assigning seating positions to children in the class. They found that multitouch capability led to more equitable participation and that children tended to interact all over the table, with more attention paid to areas closer to where they were located. These findings are similar to those in the studies looking at single-display-groupware versus mouse sharing. Later, Rick et al. presented a study looking at collaborative patterns for children using an interactive tabletop application. The study looked in depth at three cases of pairs of children working together and collaborating in different ways. One pair divided the task, another shared it, while a third worked in the same space (Rick et al., 2011).

Also looking at patterns of use for tabletops, Jamil et al. studied conversation patterns for groups of 11- to 13-year-old children across three conditions of table-based interaction: direct touch, pantograph interactive (a technique that enabled interacting with items in a different part of the table), and nondigital (a whiteboard with paper cutouts). The children worked on diagramming and classification tasks. The direct touch condition yielded more conversation around the topic and pedagogical method, while the pantograph technique led to more playfulness, and the nondigital table to more equitable group communication (Jamil et al., 2011).

Supporting family communications

Communications with family members are very important for children, and supporting them requires a good understanding of how they occur. Dalsgaard et al. conducted a study of Danish families to learn about communication between parents and children in order to better discover how to support it through technology (Dalsgaard et al., 2006). The study revealed commonalities and differences between the communications in these relationships and those between adult couples that were studied in previous research by Vetere and collaborators. For example, they found that the relationships are unequally balanced, with parents playing the role of protectors, usually seeking more disclosure from children than what they provide, and that important communications tend to occur in settings provided by parents (Vetere et al., 2005). Perhaps in part due to these constraints, family communication setups have often involved innovative solutions, such as the family calendars developed by Plaisant et al. (Plaisant et al., 2006), and the communication through home appliances designed by Kim et al. (S.-H. Kim et al., 2004).

Remote communication and collaboration

While it is not very common to use computer devices to facilitate face-to-face communication or collaboration, it is much more common for them to help children connect with remotely located people. Video calling technologies such as *Skype*, *Google Hangouts,* and *Apple FaceTime* are common ways for children to communicate with loved ones who are far away and there is evidence that such uses of technology by children have high-levels of acceptance among parents (McClure et al., 2015). Together with these commercial efforts has been a significant amount of research on technologies with the same goal, but with features that go beyond simple video calls. At the same time, children are increasingly using social media technologies, some designed specifically for them, although these have come primarily from industry instead of research.

Family communication

For many children, their most common context for collaboration is with their family members. Over the years, many research projects have focused on technologies to support families. Isola and Fails conducted a survey of research presented in the IDC and CHI conferences with a focus on families (Isola & Fails, 2012). Similar to Yarosh et al. (Yarosh et al., 2011), they found an increase in the participation of families as testers, and even as users, with fewer examples of family participation as informants, and even less so as design partners. In terms of themes, the most common was communication, either remote or co-located (often asynchronous). The authors also uncovered a growing publication trend with child-computer interaction research shifting from the CHI to the IDC conference over time.

Looking at the needs for children's remote communication, Yarosh and Abowd discussed opportunities for designing systems to help with parent-child communication in families that are geographically separated. Through interviews with 14 pairs of parents and children (age 7 to 13), they found that parents tend to focus on maintaining a constant presence in the life of the child, while children try to get emotional support from family or friends nearby, and prefer to wait for a reunion to engage more deeply with their remotely located parent (Yarosh & Abowd, 2011). In a similar study undertaken with grandparents, Forghani and Neustaedter found that grandparents try to carefully navigate social challenges, making sure they do not annoy parents or grandchildren by asking too many questions or interfering too much in their lives. They suggested systems that engage grandparents and grandchildren should take this into account (Forghani & Neustaedter, 2014).

Many of the systems implemented by researchers attempt to provide these sought-after connections remotely. The most common strategy used is to add a shared activity on top of video communication of the sort provided by commercial systems. These shared activities have included play, both with physical and screen-based items, and reading.

An example of using shared activities with physical objects comes from Yarosh et al., who developed *ShareTable*. *ShareTable* augmented videoconferencing with a camera and projector that could be used to share physical objects. In a study with seven parent-child pairs with 7- to 10-year-old children, the researchers found that the participants preferred using *ShareTable* to videoconferencing (Yarosh et al., 2009). A later field study with four divorced households (Yarosh et al., 2013) provided evidence that *ShareTable* was easier to use than the phone or videoconferencing, and enabled a range of useful communications. At the same time, it also brought about privacy concerns and new conflicts regarding calling practices. Another example of this approach came from Freed et al., who studied the use of tangible characters to help children communicate and play remotely with other children (Freed et al., 2010). The setups involved two play settings, one for each child, which included both characters and dollhouses. The system enabled children to share items remotely, by having them scanned on one end and printed on the other. It also enabled them to use a video feed to share their play settings with each other.

In terms of activities delivered through video, rather than creating complex screen-based applications, the tendency has been to use video feeds in clever ways. For example, Follmer et al. explored shared videoconferencing play activities aimed at supporting remote communication and a feeling of togetherness between children and adults. The design principles behind the project included creating a shared context, providing scaffolding for conversation, limiting user interface manipulation, using open-ended play activities to share emotions, and building on existing and familiar play patterns (Follmer et al., 2010). Along similar lines, Cohen et al. studied remote active play between children and other children, and children and their parents, and found that engaged, cooperative play was more likely if the two players shared a visual scene. The study included seven pairs, with children ranging in age from 6 to 10 years old (Cohen et al., 2014).

The third common thread in this research is in terms of shared reading activities. Follmer et al. had early examples with *Story Places*, which included a child's use of a physical book with embedded sensors, with a remotely located adult having access to an electronic version. It also enabled children to immerse themselves in the story by showing up in the video as digital representations of themselves dressed up as one of the characters in the book. *People in Books* was a second reading activity by the same research group, which involved purely electronic books that again enabled both adults and children to become part of the book, with their faces appearing in the pages where characters were located (Follmer et al., 2010).

Raffle et al. followed a similar trajectory, from physical-combined-with-digital to purely digital book reading. Their first approach, *Family Story Play*, was a system designed so grandparents could conduct dialogic reading activities with their grandchildren remotely (H. Raffle et al., 2010). Dialogic reading includes reading to the child and involving the child in the story by asking questions (e.g., “what do you think will happen next?”). The system included a paper book, a videoconferencing screen, another screen showing content from a popular television program for young children, *Sesame Street*, that was used to guide children on what to do, and sensors embedded on a frame that held the other elements. The researchers completed a study comparing *Family Story Play* to *Skype* with children ages 2 to 4 years old and their grandparents. They found that, on average, sessions were longer with their system, although grandparents and children were more likely to be on different pages twice as often when using *Family Story Play*.

The switch to a purely digital platform came with *StoryVisit* (H. Raffle, Revelle, et al., 2011). In *StoryVisit*, children and grandparents shared an electronic book on the screen, which avoided the page coordination problems with *Family Story Play*. The software also showed a video feed of both the child’s and the grandparent’s webcams. Additionally, *StoryVisit* enabled shared pointing, with each individual able to show the other what they were pointing at with a cursor, provided grandparents with tips on questions to ask for facilitating dialogic reading, and incorporated videos of Elmo, a popular television character, asking questions or making comments about book content. An evaluation of the available features with 57 families with a majority of children under the age of 4 found that the addition of Elmo to support dialogic reading resulted in longer reading sessions, and that 3-year-old children were the most engaged in the reading activities.

Also enabling remote reading to children, Boffi presented the design of the *Storybell* robot, intended for a community of older adult readers to read books remotely to children. The physical representation of the robot enabled remote awareness of when the children were interested in listening to a story, and when community members were ready to read (Boffi, 2020).

In spite of the surge of synchronous communication technologies, there is also the option to communicate asynchronously. For example, Raffle et al. (2011) studied the design of asynchronous messaging systems for preschoolers. The setup, with a box shaped like a toaster that popped out a smartphone, enabled children to take self-portraits and share them with remotely located family members. Another variation, themed around the *Sesame Street* character Elmo, enabled children and relatives to record and share short videos. The researchers also conducted observations of 30 children using the system, leading to the following recommendations: the user interface for children needs to be playful and provide a feel of real-time interaction (even if it is asynchronous), while the adults' user interface should engage them by including meaningful feedback from children (H. Raffle, Ballagas, et al., 2011).

Teh et al. had a very different take on remote communication from other researchers, putting an emphasis on tactile communication. They developed *Huggy Pajama*, a system that made use of a small doll that could be hugged, and pajamas that could reproduce the feeling of being hugged (through inflatable areas and heating elements). A parent could then hug the doll, and their child would feel their hug remotely (Teh et al., 2008).

Communication with parents through technology can also occur in situations when children live with their parents. Vacca, for example, studied the design of a meme creating tool for Latina teenagers in the United States to communicate with their parents to challenge parental assumptions or stereotypes (Vacca, 2019).

Communicating across cultures

While there has not been as much work in helping children communicate across cultures and countries, there are growing possibilities due to the increasing ubiquity of computer technologies across the world. Sharma et al. have been pursuing this opportunity by studying learning scenarios bringing together Indian and Finnish children (K. Sharma et al., 2019; S. Sharma et al., 2018). This exploration led both to new ideas for incorporating feedback from low-income Indian children through dramatizations

(S. Sharma et al., 2018), as well as identifying challenges in inclusive, cross-cultural, collaborative learning, such as differences in computer skills, video gaming experience, and socio-cultural communication norms (K. Sharma et al., 2019).

Online communities and social networking

While mostly a phenomenon for teenagers and young adults, social networking websites and online communities are also available for children under 13 and have been very popular. In contrast to other research on collaboration and communication, there is very little scholarly research in this subject, with the leading examples being commercial ventures, and research being limited to examining these technologies.

Some of the few examples from researchers include Bruckman's work on *MOOSE Crossing*, an online community for children to learn about object-oriented programming and to practice creative writing (A. S. Bruckman, 1997), and Kaplan and Chisik's work on collaborative reading and annotation of online books (Kaplan & Chisik, 2005). Later, Inkpen et al. presented *Video Kids*, an asynchronous system for video communication designed for children to communicate with their friends. The app enabled a small group of friends to share video instead of text messages on topic threads. A pilot trial with a group of 9- to 10-year-old girls saw a significant amount of use including conversations, show and tell, sharing, screen recording, performances, and fun videos (K. Inkpen et al., 2012).

On the commercial side, early examples of online communities targeted at children included *Neopets*, *Club Penguin*, *Webkinz*, *Nicktropolis* (later *The Club*), *Fantage*, and *BarbieGirls*. These online communities were quite popular: as early as 2003, for example, *Neopets* claimed 16 million users (Grimes & Shade, 2005). These online communities gave children the ability to create an avatar that they could use to explore a virtual world. The virtual worlds included games as well as the ability to chat with other children. In the virtual worlds, children could obtain accessories or buy improvements for their avatars or themselves. These require spending money on monthly fees or credits that can be transferred online, or can be obtained by participating in games that include advertising, or by completing market surveys (Grimes & Shade, 2005). There are also offerings that attempt to provide experiences similar to those on adult-oriented social networking sites. Examples include *spotlite* (similar to *Instagram*) and *GoBubble* (social communication for school settings). Of course, many children also use popular networking sites designed for adults by lying about their ages, and often without a full understanding of how to use them safely (Livingstone et al., 2013). In addition, many videogames now include chatting and other social features as part of online multiplayer capabilities, which also get children in contact with others online. An observation of note is that the social networking services designed for children have tended to be short-lived when compared to their cousins designed for adults.

There have also been explorations of social network use by teenagers and how this group manages and explores their digital and physical identities. In Chapter 7 we covered the research by McRoberts and colleagues on teenage use of *YouTube*, including audience engagement practices (McRoberts et al., 2016, 2019). Emanuel and Stanton Fraser took a broader look as they conducted three workshops with young people in the United Kingdom ages 13 to 18 years old. Among the findings were concerns about strangers accessing personal information, awareness of the permanent status of online communications versus the ephemeral nature of face-to-face communications, and no clear agreement on future ways of providing identification (i.e., online authentication) with both proposals and concerns about biometric information (Emanuel & Stanton Fraser, 2014). Vacca studied the potential roles of social networks in supporting the emotional health of Latina teenagers in the United States, finding that most of the needs expressed by the teens could be addressed with existing technologies if they could be adapted to manage cultural norms and practices (Vacca, 2017).

Other researchers have explored the use of online communities to support children's health. This topic is covered more extensively in Chapter 11. An example is research from Bhattacharya et al. on the use of asynchronous remote communities by teenagers for the purpose of stress management. The teenagers in the study appreciated the flexibility of the system they used, but interactions between teenage users were limited (Bhattacharya et al., 2019).

Safety and privacy

The widespread use of technologies connected to the internet and targeted at children has sparked novel research during the latter half of the 2010s on children's safety and privacy. Topics include children's perception and practices on safety and privacy online, educating children about these topics, co-designing safety and privacy tools with children, bringing awareness to the use of dark patterns in children's apps, and the role of parents both in managing children's technology use and in disclosing children's information.

In commercial online community systems designed for children, in order to increase their safety, some ideas that have been used include limiting chat to preset phrases, moderating content, and communicating only with white-listed contacts. In some cases, children's profiles are limited to sets of likes and dislikes that often involve products promoted by the sites (e.g., *Nickelodeon* characters). At the same time, many free-to-play apps for children incorporate dark patterns that involve various types of deception (Fitton & Read, 2019).

In terms of children's perceptions, which are changing and will continue changing, studies have tried to understand what privacy means to children and what they perceive as threats. Zhang-Kennedy et al., in research with 14 families found that children identified privacy with being alone, keeping secrets and personal information from others, and not communicating with strangers (Zhang-Kennedy et al., 2016). In the same study children saw threats in peers (e.g., siblings), bad media, mean strangers, and parents (Zhang-Kennedy et al., 2016). Kumar et al. reached similar conclusions in research with 18 families, although they found that children under the age of 9 had greater difficulty understanding the implications of sharing information online (P. Kumar et al., 2017). By 2019, Zhao et al. found that 6- to 10-year-old children were well aware of privacy risks such as information oversharing and revealing their real identities online, but were less aware of less visible issues such as online tracking (Zhao et al., 2019). Teenagers have greater awareness of privacy risks as Potapov and Marshall found through co-design activities, learning about tensions between privacy, social support, flexibility, and self-expression (Potapov & Marshall, 2020).

Given the gaps in children's knowledge about privacy and security risks, some researchers have studied how to educate children about the topic. A group from the University of Maryland worked with 8- to 11-year-old children to co-design educational interventions. They developed recommendations including using storylines and familiar characters, educating children on how to make privacy-related decisions, and exposing them to possible privacy consequences of online behavior (P. Kumar et al., 2018). Working with teenagers, Dowthwaite et al. developed a card-based activity to bring awareness of how personal data may be acquired and sold by online companies and recommend the inclusion of similar activities in school curriculums (Dowthwaite et al., 2020). Also thinking of teenagers, Yap and Lee proposed a framework for teaching about privacy issues including gaining awareness of privacy issues, understanding how data-centered technologies work, reflecting on their own behavior, and learning about safer ways to act (Yap & Lee, 2020).

In terms of how tools can be designed to help children manage safety issues, Badillo-Urquiola et al. conducted research with 8- to 11-year-old children to understand their interests with respect to risks related to interactions with strangers. They learned that children preferred to have more control over low-risk situations, while they were willing to get help for more serious situations (Badillo-Urquiola et al., 2019).

Some populations may be at greater risk than others, such as foster children in the United States. Badillo-Urquiola et al. studied views on these children's online safety concerns, including tensions between providing access versus keeping children safe from risk and the lack of privacy and safety tools that take into account this group's needs (Badillo-Urquiola et al., 2017).

Parents often play a role in children's online safety, but tend to have views that are not always compatible with children's views of online safety. Rode conducted an ethnographic study to learn how parents attempt to keep children safe online. Common approaches included monitoring children's actions with and without the use of technology, using software to block certain activities, conversing with children about safe behavior while encouraging self-restraint, and discussing safe behavior while allowing curiosity. Children seemed less concerned than parents overall, although some had specific concerns about identity theft, unwanted intrusions by strangers, and inadvertently downloading viruses (Rode, 2009).

Also studying parental perspectives, a small survey in the United States found parents' concerns about children's addiction to technologies and children making poor choices due to lack of experience are not necessarily shared by children (Zhang-Kennedy et al., 2016). Kumar et al. found in another small survey of families in the United States that their typical parental practices included setting boundaries (e.g., apps not allowed), maintaining ambient awareness (e.g., ask that devices by used in a common area), using built-in parental controls, and monitoring children's devices (P. Kumar et al., 2017). A larger discussion in Finland revealed tensions between monitoring and control by parents and building a trusting relationship (Hartikainen et al., 2016). In the spirit of building a trusting relationship, Hiniker et al. designed *Plan & Play*, an app that enabled young children (4 to6 years old) and parents to plan app use together. In terms of children's views on parental control apps, Kumar Ghosh et al. found that children's reviews of these apps were overwhelmingly negative, with children complaining about them being overly restrictive and invasive of their privacy (Ghosh et al., 2018). A co-design exercise with children aged 7 to 12 found that their preferences around parental control software focused on restriction over monitoring, helping them assess risk, and promoting parent-child communication (McNally et al., 2018).

Parents and other family members can also be guilty of violating children's privacy when they post about their children online (Ammari et al., 2015). Note that current social networking technologies do not enable children to retroactively manage content shared about them once they are old enough to do so. Through a survey of 331 parent-child pairs in the United States, Moser et al. found that children would like their parents to ask for their permission more often before posting about them online. Children in the survey also noted that they did not like it when parents posted anything embarrassing or overly revealing (Moser et al., 2017).

Interacting with artificial intelligence systems

While the bulk of the research on communication and collaboration is about interactions with people, during the latter half of the 2010s there was an avalanche of research with the goal of informing the design of or evaluating children's interactions with Artificial Intelligence technologies. These technologies include intelligent agents, voice assistants, robots, and smart toys. This new focus has been brought about to a great degree by increases in the ability to capture data through a range of sensors, and in storage, processing power, and communication speeds. These changes have enabled advances in Artificial Intelligence to be delivered to a wide range of users, including children.

This area of research has opened up a significant new set of opportunities as well as an ethical minefield. The opportunities are for communication with technology through natural language and embodied interactions that may be more appropriate for children in some circumstances, for a different kind of relationship with technology, and for a high level of personalization and guidance. Ethical issues include the need these systems typically have for highly-invasive data collection as well as these technologies taking the place of caretakers, teachers, and friends (Hourcade et al., 2018). The need for highly-invasive data is based on the observation, identified by Woodward et al., that in order for children to consider a technology to be intelligent, it needs to be able to react properly to the socio-physical context (Woodward et al., 2018). Work has moved quickly in this space, with datasets and analyses of data needs available to design interactions that recognize children's socio-emotional state (Esposito et al., 2015; Nojavanasghari et al., 2016; Santos et al., 2020; Singh et al., 2018).

Children can interact with various forms of agents, which can range from voice assistants, to screen-based agents, to various forms of physical objects, including robots. There is evidence that at least some groups of children prefer agents with a physical rather than virtual representation (Pantoja et al., 2019b; Spitale et al., 2020).

Voice assistants

Commercial voice assistants, such as *Amazon Echo* and *Google Home,* have been making their way into many homes and with their arrival, children are using them. A series of studies has shed light on how children are using these systems. Their findings suggest that children typically use commercial systems to explore interactions, seek information, or make requests (e.g., for media to be played) (Druga et al., 2017; S. Lovato & Piper, 2015). However, these interactions were usually marred by poor speech recognition (Druga et al., 2017; S. Lovato & Piper, 2015; Sciuto et al., 2018) and difficulties communicating (e.g., getting questions answered) (Cheng et al., 2018; S. B. Lovato et al., 2019; Yarosh et al., 2018). There are also hundreds of voice-based apps marketed as learning apps for children (Y. Xu & Warschauer, 2020a), as well as experiences in designing educational apps from researchers (Y. Xu & Warschauer, 2020b).

Screen-based agents

Screen-based agents have been used for some time in learning applications, but can also be available in other settings. One area where they come up is in apps that feature characters from children's television. Researchers in educational television, for example, look to design for parasocial relationships between children and characters across linear video, interactive media, and the use of agents in order to make educational media more effective (J. H. Gray et al., 2017). Others have developed age-based guidelines for the design of animated characters (Carter, Mahler, et al., 2016). There is evidence that animate characters can be useful for quick, fun interactions. For example, Tewari and Canny developed a system to engage preschool children in a question-answer game. In the game, the children interacted with an agent in the shape of a dog who wanted them to guess an object in 20 questions. Children would ask yes/no questions and the dog would answer. The children seemed engaged with the system, and the simplicity of the interactions made it so even an automated system had adequate performance (Tewari & Canny, 2014).

One thing not to do is to use realistic-looking, computer-generated faces as children have a clear preference for interacting with real people over these computer-generated characters (Hyde et al., 2014).

Smart toys

Smart toys have been available for some time, with an early example being *Actimates Barney*, which worked when VCRs were still the main way to access video (E. Strommen, 1998). This early project made efforts at making similar toys into social interfaces that make use of humor, praise, and affection (E. Strommen & Alexander, 1999). Later on, Luckin et al. found these stuffed animals to fall short in terms of being useful collaborative learning partners, but at the same time they noted that children had no problem learning to interact with them (Luckin et al., 2003).

During the latter half of the 2010s, the focus has been on understanding how children interact with toys that typically come in the form of a character and enable children to engage in conversations and how smart toys may be perceived (e.g., (Druga et al., 2018)). McReynolds et al. conducted a small survey of families to learn about how children interact with smart toys. They found that children play through built-in voice-based activities (e.g., ask a toy to tell a joke), could understand the limitations of the toys (e.g., inability to answer certain questions), parents had some concerns about toys recording audio, and children were surprised that their interactions with their toys were shared with the companies that made the toys (McReynolds et al., 2017). Other researchers have thought about design futures for interconnected toys. Zaman et al. propose taking an animistic design perspective where interconnected toys act with a level of uncertainty, as opposed to providing predictable outcomes (Zaman et al., 2018).

On a somewhat different note, Ackermann surveyed the different ways in which toys may be perceived as being animated or smart. She identified successful toys of this type to have the attributes of being perceived as artificial (i.e., not alive) consistent in ways of being and doing and having the ability to engage in dialogue while maintaining their own characteristics. Ackermann saw these toys as letting children explore a variety of interactions without hurting or getting hurt, and learning about individuality as well as limitations and alternative ways of getting something or someone to do something (Ackermann, 2005). These ideas could be used to inform the design of engaging characters, while at the same time making it clear to children that these characters are artificial.

Robots

It may be difficult to clearly define a line separating smart toys from robots, but the idea is that the latter typically have more actuators, in particular enabling them to move. Some areas of research overlap with other artificial intelligence systems, such as challenges with speech recognition (Kennedy et al., 2017), with communication (Serholt, 2018), and concerns about privacy and confidentiality due to the use of sensors (Cagiltay et al., 2020).

There is also evidence that children do not prefer robots that resemble humans. Woods conducted a study to understand 9- to 11-year-old children's reactions to the visual design of robots. She found that children had very negative views of robots that resembled humans but could still be distinguished from humans (a.k.a. the uncanny valley). Children preferred a mixture of human and machine-like visual features (Woods, 2006). With such robots, there is evidence of children showing short-term social interest in the robots (Serholt & Barendregt, 2016).

Most of the research on robots and communication has focused on establishing richer relationships between children and robots. For example, Kocher et al. studied how simple autonomous capabilities displayed by a robot could elicit children to help the robot (Kocher et al., 2020). Cameron et al. found that life-like robot facial expressions resulted in some children showing greater positive affect toward a robot (Cameron et al., 2015). Others have focused on establishing long-term relationships between children and robots. Ahmad et al. found that robots that made emotional adaptations and remember past events were more likely to lead to longer-term engagement (Ahmad et al., 2017). This finding is consistent with Leite et al.'s study finding children preferred robots that remembered past interactions (Leite et al., 2017), although the same group found the opposite result when robots knew things children did not expect them to know (Leite & Lehman, 2016). Looking to further investigate the topic, Westlund et al. developed an assessment instrument to measure children's long-term relationships with robots (Kory-Westlund & Breazeal, 2019; Westlund et al., 2018)

We can also learn from children about their conceptualization of robots, as Malinverni and Valero did with a group of eight 10- to 11-year-old children. During a workshop, this group of children gave robots human or animal-like characteristics, assigned gender and associated stereotypes to the robots, and established a relationship between robots and violence (Malinverni & Valero, 2020). While these children were not necessarily a representative group, given the way robots are portrayed in popular media, caution may be necessary in order to avoid negative stereotypes if co-designing or using robots with children.

Summary

Communication and collaboration play a very important role in children's development. Researchers and commercial ventures have developed technologies to support communication and collaboration at various levels, including face-to-face, remote, and through social networks.

Support for face-to-face collaboration began with setups that connected multiple pointing devices to the same computer. These setups provided advantages over setups in which children had to share a computer with only one input device.

Researchers have observed similar patterns with touchscreens, where multitouch capabilities lead to better collaboration and communication than touchscreens that can only process one touch at a time. In addition, different patterns of collaboration may arise, depending on how the rules for collaboration are set up, and on the personal characteristics of those communicating or collaborating.

There is also a significant amount of research on supporting remote communication. Most of it is intended to help children connect with loved ones who are far away. These efforts have gone beyond videoconferencing applications by, for example, providing additional support for playing or reading books together.

Commercially, there are many social networking applications for children, with a variety of features to keep interactions with others safe. At the same time, these often include advertising and may collect marketing data from children. Children also use a variety of apps that may collect data and parents share about children, which has sparked a new subarea of research on children's online safety and privacy.

Children are also beginning to interact more often with artificial intelligence systems, including voice assistants, smart toys, and robots. Research on these systems has studied children's communication with commercial systems, opportunities for new types of communications, and the factors affecting how children feel about and engage with these devices.

Given the importance of communication and collaboration in children's development, this is likely to remain an active area of research. The challenge will be to balance the pursuit of new opportunities for remote communication with enhancing already existing face-to-face communications, while ethically managing children's safety and privacy.

Chapter 9
Accessing Media

With editorial feedback from Meryl Alper, Northeastern University

One of the main advantages computers can bring to children is access to content they would otherwise not encounter. These possibilities have been enhanced by the Internet, which allows children to access an enormous amount of media from a wide variety of sources. Children today have more content at their fingertips than would have been available at all physical libraries in most countries in the 1980s. Touchscreen devices have enabled even very young children to access digital media (Hourcade et al., 2015). Computers also provide new ways of capturing, gathering, annotating, and organizing information.

A significant challenge though is that most technologies for accessing digital content have been designed with adults in mind, which in some cases brings about challenges for children. This chapter features research from the child-computer interaction community on topics such as search engines, digital libraries, media annotation, and interactions with complex media.

Browsing, searching, gathering, and organizing content

Search engines

World Wide Web search engines have the potential to be powerful tools for children, but their heavily text-oriented design can reduce their usability. In particular, search engines rely on their users having a minimum level of typing, spelling, and reading ability. In addition, sophisticated search skills (e.g., how to exclude certain results, how to limit a search to a particular domain) may be difficult for children to learn. A final problem is that it may be difficult for many children to understand text-based results that may include many documents prepared for an adult audience (e.g., more advanced vocabulary).

Druin et al. conducted an early study looking at how children used search engines. Through the study, with 7- to 11-year-old children, the researchers found the main barriers to effective use to be in spelling and typing mistakes, formulating queries, and understanding results (Druin et al., 2009). Hourcade and Perry found similar challenges, including the difficulty of finding relevant information in a relevant document (e.g., a specific fact in a Wikipedia document) (Hourcade & Perry, 2009).

In a follow-up study, Druin et al. looked at children's search strategies at home. The study included 83 children aged 7, 9, and 11. Druin et al. identified seven search roles among the children: developing searcher (a novice who tends to use natural language), domain-specific searcher (who limits searches to domains of interest), power searcher (one with sophisticated skills), non-motivated searcher (who is not interested in searching), distracted searcher (who easily gets distracted and does not complete search tasks), visual searcher (who prefers to search within a visual context), and rule-bound searcher (who knows a few search tricks or rules and applies them when searching). Based on these findings, they recommended that future search engines take into account children's interests, scaffold known challenges, provide help at the right time, support multiple types of input (e.g., images), and make an effort to show results that are relevant to children (Druin et al., 2010).

To better design for children, it may also be advantageous to learn how they differ from adults. Gossen et al. presented an eye-tracking study comparing the use of *Google* and a German educational search engine (Gossen, Höbel, et al., 2014). The study compared use by adults and 8- to 10-year-old children. They found that children tended to scan more results on a page, focusing more on thumbnails and less on text summaries. Adults tended to focus on the first three results, and if these were not satisfactory, they would reformulate the query. These findings again suggest that more visual results with options specifically tailored toward children may be most useful. Gossen et al. proposed representing web pages as characters that would provide visual clues about the content of the pages (Gossen, Müller, et al., 2014).

Others have focused on helping children learn better search strategies. Moraveji et al. developed a system called *ClassSearch* to help children aged 11 to 14 in a classroom environment. The system included a shared display that provided awareness of the search terms others were using, and the websites others were visiting, without identifying specific children. The system also enabled teachers to see queries and pages visited by individual students. The idea behind this type of system is that through the combination of awareness of a variety of strategies and teacher feedback, children may be able to more quickly learn the types of strategies that yield the best results. These approaches would have to be incorporated with appropriate pedagogical approaches, however, to avoid having children copy what others do without understanding why it works (Moraveji et al., 2011).

In spite of several efforts and improvements in text-based search engines to make them more accessible and address some barriers (e.g., spelling), challenges remained at least as of the late 2010s. Fails et al. found that existing plug-ins to aid with query formulation and query suggestion strategies failed to meet children's expectations. They suggest providing visuals in search results to enable children to quickly realize whether their query worked as intended, having query suggestions be influenced by contextual information (e.g., time, location), and differentiating query suggestions from spelling corrections (Fails et al., 2019).

An alternative to traditional text-based search that has become more common beginning in the late 2010s is voice search, enabled by voice assistant technology available in a wide range of devices. The challenge with this approach to search, as covered in the previous chapter, is that speech recognition can still be challenging for young children's voices. In addition, it may not be clear to children how to reformulate queries that do not return expected results (Yarosh et al., 2018). Other proposals to improve voice assistants for children include tailoring answers to children of specific ages, simplifying answers so they are succinct and direct, using the context of previously asked questions, and adapting responses based on repetitive questioning (S. B. Lovato et al., 2019).

A type of media interaction that is often accessed through web searches is maps and directions. A limitation of current interactive map and wayfinding applications is that they have been designed for adults. Silva et al. conducted design activities with 70 9- to 12-year-old children to identify design requirements for geographic technologies for children. They identified four categories of landmarks that children used in self-produced maps: newness, cultural personalization, infrastructure, and natural landscapes (Silva et al., 2020).

Digital libraries

Since a majority of the content on the Internet was not developed for children, it can be convenient to develop curated collections of content that are designed specifically for them. This is the realm of digital libraries. One of the best-known examples of digital libraries for children is *The International Children's Digital Library* (ICDL), available at www.childrenslibrary.org, providing children with access to thousands of books from dozens of countries in dozens of different languages with age-appropriate interfaces for finding and reading books of interest (Druin, 2005; Druin et al., 2007; Hourcade et al., 2003; Hutchinson et al., 2006). It provides a searching and browsing interface for elementary school children that eliminates the need to navigate classification hierarchies (Hutchinson et al., 2006). It was designed based on the experiences of the *SearchKids* project (Druin et al., 2001). Kaplan et al. used the *ICDL* as a starting point to learn how it would need to be adapted for teenagers. They found that teenagers wanted to personalize the look of the user interface, conduct text searches over the collection and within books, and share annotations of books with groups of friends and classmates (Kaplan et al., 2004).

Other work on digital libraries includes that of Abbas et al., who reported on middle school children’s interactions with a digital library of web resources to support children’s scientific inquiries (Abbas et al., 2002). The web-based library was designed following the Learner Centered Design model, which emphasizes the use of scaffolds to support and provide structure to children in their learning activities (Soloway et al., 1996). Eriksson and Lykke-Olesen developed a library catalog for the children’s section of a library that children could browse by stepping on options on a large mat. In this case, the idea was to make searching and browsing the catalog a more playful and physical activity (Eriksson & Lykke-Olesen, 2007).

App stores and other venues for acquiring digital content share commonalities with digital libraries in terms of having a curated collection to search and browse. One challenge in designing them, which is also present in digital libraries, is understanding how to classify items. One technique often used for designing classification systems for adults is card sorting, whereby design team members ask prospective users to classify items into piles and optimal groups are obtained from these piles. Cassidy et al. conducted a card sorting exercise with children ages 8 to 10 to learn about their preferences for classifying mobile phone games. The researchers found that children preferred to categorize games based on the primary activities involved in the games. In some cases, their classification matched existing categories for adults, such as sports and racing. However, they included other categories such as building and running away, and did not include categories such as arcade or action games (Cassidy et al., 2013). This result is similar to findings in the *ICDL* project where children classified items differently from adults (Hourcade et al., 2003). Any browsing system should take into account children's item categorization preferences.

As children browse content, one challenge is helping them identify which content is appropriate versus inappropriate. This is particularly concerning to parents. Attempting a solution to this problem, Hashish et al. studied collaborative filtering of apps, with the objective of helping children understand how their parents made decisions on which apps were appropriate. The authors set it up as a game and found that 4- to 10-year-old children found the game engaging and were able to learn about the types of apps their parents approved and disapproved (Hashish et al., 2014).

Tangible user interfaces and search

Researchers have used tangible user interfaces to make abstract concepts more concrete for children. Using this idea in the realm of conducting searches, Gorbet et al. developed a tangible user interface for accessing and manipulating information based on triangles that represented query components and could be physically connected (Gorbet et al., 1998). Attempting to simplify access to contact lists for teenagers, Labrune and Mackay developed prototypes for a system that incorporated technology into jewelry. They enabled the association of specific pieces of jewelry with an individual or group (e.g., an earring corresponding to a specific friend) (Labrune & Mackay, 2006).

Annotating and interacting with digital content

Once children find content, it is also important that they have developmentally appropriate ways of interacting with it. This can involve annotating the digital content, which can be useful for later reference, as well as for learning in group environments.

In the world of digital libraries, for example, it may sometimes be useful for children to be able to annotate digital books, just like they would annotate physical books. These annotations could be even more useful if they could be shared within small groups. Working with teenagers, Kaplan and Chisik augmented a book reader with “stamps” expressing questions, joy, sadness, ideas, or calls for attention. These stamps could be associated with sticky notes that included text. Children had the option of sharing each annotation with other children reading the same book (Kaplan & Chisik, 2005). Through a study, the researchers found the children made ample use of annotations, sometimes even responding to questions others posed (Kaplan et al., 2006). Working with younger children, Colombo and Landoni found that an enhanced digital book (i.e., interactive, with embedded multimedia) provided a better user experience for 7- to 12-year-old children than digital books consisting of scans of print books, especially through a read-aloud feature (Colombo & Landoni, 2014). In terms of what media to embed in books, Wang and Chiu examined the types of illustrations that may work best for retaining content (H.-F. Wang & Chiu, 2020), while Alhumaidan et al. explored the use of augmented reality (Alhumaidan et al., 2018). In spite of all the ongoing research, commercial systems still lag behind, according to Roskos et al. who found a focus on text access and word learning as opposed to comprehension and media integration (Roskos et al., 2017). Another issue identified by Xu et al. with commercial systems was difficulty, in particular for children under the age of 4, in navigating eBooks by turning pages (Y. Xu et al., 2019).

A type of media that may soon see opportunities for interaction is young children’s television. Children’s television has made use of characters asking children questions and pretending to wait for an answer since at least the 1990s. Researchers are now considering any additional benefits from adding true interactive content, where characters may repeat unanswered questions and provide timely feedback to children on their responses. Carter et al., for example, found that continuing a children’s program after children either responded or 10 seconds had gone by elicited more responses from children when compared to the typical 2-second pause used in current programs after a question. They also found that re-prompting children who do not answer the first time helps elicit children's responses and that providing feedback to children's answers did not affect response rates or content retention (Carter et al., 2017).

Sometimes a way to better engage with a story is to make something that becomes part of the story. Following this concept, Bodén et al. combined tangibles with augmented reality in *Save the Wild,* a system intended to help children learn about environmental sustainability issues. The system enabled children to make origami paper characters that could be augmented with markers recognized through computer vision. As children brought their characters to the camera, they would see them represented as animated virtual characters on a display, where they would become part of simple storylines about sustainability. The setup was successful when tested at a public exhibition and in a classroom with 5- and 6-year-old children (Bodén et al., 2013).

Museums are a space where children are increasingly encountering digital content. Hall and Bannon provided guidelines for interactive museum exhibits. They recommended using a compelling narrative, making the exhibit inviting, allowing children to contribute to the exhibit, making sure technology does not get in the way of the experience, providing multi-sensory experiences, supporting both individuals and groups, supporting exploration, and incorporating the participation of experts (T. Hall & Bannon, 2005, 2006). An example that implements many of these recommendations comes from Kourakis and collaborators, who developed an interactive multimedia app to enable children to learn about prehistoric art and the scenes it depicted. The setup used a multitouch screen that used predefined gestures as inputs. Children could then interact with the art shown on the screen, with the figures based on the original art responding through animations (Kourakis et al., 2012).

Archives are often part of museums, in which case there may be choices as to whether to present them in physical or digital form.

Jones et al. (2012) studied different ways of presenting archive photographs to children. In a study comparing presentation of real photographs, digitized images on a tablet, and digitized images on a large display, children (9 to 10- years old) had greater emotional responses to the real photographs (assessed through a frowning–happy face questionnaire), but at the same time had greater cognitive responses to the images on tablets (they could write more ideas about the image). This finding suggests combinations of physical and digital archives may yield the best results (S. Jones et al., 2012).

Summary

Internet connectivity has significantly increased the amount of content children can access and decreased the effort it takes to access it. At the same time, user interfaces for searching, browsing, organizing, and experiencing content need to be developmentally appropriate. In particular, designers need to be aware of the challenges many children face in typing, spelling, and reading, as well as their search strategy skills. They also need to consider the types of categorizations that make the most sense to children. If possible, user interfaces should incorporate social aspects that can help children learn together and from one another. Voice assistants provide new opportunities to aid children in searching, but they are still limited.

Once children encounter digital content of interest, it may be useful to provide them with options to annotate the content, and share these annotations with peers. There is still active research on improving reading in electronic formats, as well as opportunities to provide interactivity to other traditional formats such as children's television. One area where children are increasingly encountering digital content is in museums. Research from the child-computer interaction community has contributed guidelines for the design of child-appropriate exhibits, as well as examples of such exhibits.

All these guidelines can help steer future media technologies to cater not only to adults, but also enable children to access media in a developmentally appropriate manner.

Chapter 10
Learning

How can computers help children learn specific skills or information? How can interactive learning technologies be integrated with school curricula? The promise of learning gains from computer use often entices educators and politicians to make significant investments in computers. Traditionally these investments took the form of computer labs, while since the 2010s, laptop programs have become more common. The COVID-19 pandemic in the early 2020s has accelerated the process of incorporating computers into children's formal schooling and bringing them to children's homes. This chapter discusses research on interactive learning technologies from the child-computer interaction field only, although there is certainly a much wider set of research on this topic, primarily from the learning sciences. Because the work presented below comes primarily from the child-computer interaction field, it is more likely to follow constructivist and constructionist approaches, supporting children in exploration and creation. Work from other communities is more likely to feature behaviorist approaches, especially when the goal is to prepare children to take standardized tests.

This chapter provides an overview of overall guidelines for the design of interactive learning technologies, followed by a discussion of approaches to incorporate computers in schools. The chapter concludes with a discussion of learning technologies geared at specific areas including reading, writing, mathematics, science, and technology.

Overall guidelines

Some of the foundations for interactive learning technologies were laid by Soloway et al., who have conducted many projects on learning technologies for children using an approach called learner-centered design. The premise is that learners have three unique needs that need to be addressed by these technologies: growth (learning by doing), diversity (not everyone will arrive with the same set of skills), and motivation. These can be addressed through the use of scaffolds, for example, by providing structure to a scientific inquiry task (Soloway et al., 1996). Focusing on children with disabilities, Flórez-Aristizábal et al. presented a design framework called *DesignABILITY* involving four phases: identifying learning requirements and strategies, designing for engaged learning, prototyping, and evaluation (Flórez-Aristizábal et al., 2019).

Another take on guidelines for educational technologies came from Fisch, who compared guidelines for successful children's television and magazines with those for successful educational software. He identified the main differences in terms of literacy (some media requires reading skills), the need for parental or adult involvement, the ability to control the flow, the usability, and the ability to author (Fisch, 2004). Main areas in common for these two sets of guidelines included appeal, clarity, explicitness, age-appropriateness, text legibility, and visual effects. In follow-up work, Fisch outlined recommendations for the design of educational games. These recommendations included matching topics to the most appropriate media, putting the educational content at the core of the games, and providing feedback and hints as necessary to scaffold children's interactions for challenging content (Fisch, 2005). In another discussion of recommendations for educational games, Linehan et al. preferred guidelines involving the use of traditional behaviorist approaches such as positive and negative reinforcement and positive and negative punishment (Linehan et al., 2011).

It is also useful to know the barriers that may prevent children from making effective use of educational technologies, especially for young children. Plowman et al. (2008, 2012) studied the use of computers in the home for 3- to 4-year-old children through a survey of over 300 families and 24 case studies. They found that parents tended to underestimate their role in teaching how to use technologies, and instead thought that children tend to learn on their own through trial and error, copying, and demonstration. In particular, there were four areas where children could have further support when using technology: acquiring operational skills (i.e., basic ability to interact with technology, such as selecting an icon on a touchscreen), extending knowledge and understanding of the world (e.g., mathematics, language), developing dispositions to learn (e.g., confidence, independence), and understanding the role of technology in everyday life (e.g., communication, employment, entertainment) (Plowman et al., 2008, 2012). In related work, Hightower et al. investigated through semi-structured interviews with 12 parents of preschool children how parents select math and science media to share with their children (Hightower et al., 2019).

Learning with tangibles

Tangible user interfaces can be a useful approach to learning technologies and may provide advantages to younger children through more concrete user interfaces. Marshall developed a framework to guide the research and development of tangible user interfaces aimed at learning activities for children. The framework included six perspectives: learning domains, learning activity, integration of representations, concreteness and directness, effects of physicality, and possible learning benefits. He argued that using this framework can lead to a better understanding of the learning benefits of tangibles, as well as the reasons behind the learning (Marshall, 2007). Manches and Price discussed how to decide between tangible and graphical user interfaces when designing learning environments. They suggested that the choice should be based on learning goals, understanding how each approach may contribute to learning. For example, some learning needs may require more concrete representations that may work better with physical interaction, while others may require more abstract representations that may be better presented through a graphical user interface (Manches & Price, 2011).

Computers in schools

One challenge in bringing computer-based learning to schools is how to best incorporate computers in the educational setting. In the United States, for example, computer use has been shifting from computer labs to one-device-per-child programs, although these have often failed to meet expectations (Ames, 2019; Blume, 2015). Failures have occurred mainly with top-down initiatives, with devices and software that are often a poor fit for the educational ecosystem in which they are deployed. Most of the truly innovative ideas in this area have been in attempting to introduce computers to schools in low-income regions of the world.

One low-cost solution to bring computers to schools is by connecting multiple input devices to one computer. Chapter 8 includes a summary of these efforts. Another low-cost solution that has had a significant impact in a few countries is the use of low-cost laptops, with early examples including the XO from the One Laptop Per Child (OLPC) Foundation, and the classmate PC from Intel. Hourcade et al. and Flores and Hourcade illustrated early deployments of OLPC laptops in Uruguay, which included many encouraging uses, as well as some challenges (Flores & Hourcade, 2009; Hourcade, Beitler, et al., 2008). The greatest gains were brought about by device mobility and internet connectivity. Cramer et al. found similar positive findings with Intel's classmate PC. Mobility enabled the laptops to be treated almost as paper notebooks, allowing children to get help from teachers, work together, and document activities outside of school more easily. Internet connectivity enabled children to access a much wider array of text to read than what was previously available to them, making it more likely that they could find engaging material (M. Cramer et al., 2009). However, after 4 years of deployments, a large study concluded that the OLPC laptops, given to every public elementary school child in Uruguay, did not have an impact on students' mathematics or reading skills, regardless of socioeconomic status (De Melo et al., 2013). In this case, the challenges again involved a top-down approach that did not take the educational ecosystem into account. For example, teachers found a mismatch between what they could do with the laptops and what they were supposed to teach according to the curriculum. In spite of these barriers, Uruguayan teens who began programming through their use of OLPC laptops won the Google Code-In contest in 2012, 2013, and 2014 (one award per year out of 20 awards given worldwide). Other countries have faced similar challenges. For example, through observations in Mexico, Cervantes et al. found that the barriers to successful adoption of low-cost laptop devices lay in developing the social and technical infrastructures to support their use (Cervantes et al., 2011). Ames provides evidence of similar challenges in her book chronicling experiences in Paraguay (Ames, 2019).

Alaimi et al. presented an exploration of how using general-purpose laptops with integrated content could support better question asking skills in the classrooms. They integrated question prompts into the content children were covering and found that these increased the number of questions being asked and children's fluency in asking questions (Alaimi et al., 2020).

In higher-income regions, researchers have studied the use of more expensive technologies. For example, Kharrufa et al. examined the large-scale deployment of multitouch interactive tabletops in eighth-grade classrooms (with 12- to 13-year-old students). The deployment used *SMART* tables, having children use each table in groups of two to four students. The interactive tabletops were not in the regular classroom; instead, teachers brought students to a space where the tables were set up for one-hour sessions, where the students used applications designed for collaborative activities. Conducting the activities was challenging due to issues with lighting that required recalibration, problems with student behavior, and teachers not being aware of the progress of each group or of individual participation (Kharrufa et al., 2013).

An emerging trend is the use of cameras and sensors in schools with a variety of goals. When the goal is controlling student behavior, one approach has been to use these devices to track children in schools (e.g., are they paying attention?), with some systems going as far as analyzing student facial expressions (Jourdan, 2018). Such approaches are very controversial in democratic societies, but are being implemented in countries where there is already a significant amount of surveillance in society (Galligan et al., 2020). Uses of similar technology in the child-computer interaction field have paid particular attention to children's privacy while trying to promote desirable behaviors (Garbett et al., 2018) or used sensors in spaces separate from classrooms without tracking individual children's behavior over time (Garzotto et al., 2020).

A need that may not always be emphasized in classrooms is reflecting on classroom activities. Gourlet et al. developed the *Research Diary*, a system that enabled children to document activities during a particular portion of their school day, while enabling social aspects, in order to reflect on those activities (Gourlet et al., 2016).

Other digital technology can be incorporated into classrooms to support learning in unusual ways. Balaam et al., for example, presented the design of the *Subtle Stone*, which enabled children (aged 12 to 13) to express their feelings during class by operating a handheld ball that could change colors. Each student could decide on individual associations between colors and emotions. Their teacher could see the feelings of each student on a tablet, but the feelings were not revealed to classmates (unless they knew another student's color-emotion mapping) (Balaam et al., 2010).

Researchers have also begun to explore the use of robots as teaching assistants or tutors. Van Ewijk et al. consulted teachers and found that they had several concerns about their use in the classroom including privacy and security, applicability, children's psychological welfare, usability, accountability, impact on human contact, trust and deception, and safety. Teachers also saw opportunities in personalized learning, computational thinking, children's motivation, and support for children with disabilities (van Ewijk et al., 2020). Providing further evidence of the need to consult multiple stakeholders, Obaid et al. found that adult interaction designers and children had very different ideas for the basic design of robots that could work as teaching assistants in the classroom, with the adults preferring small, non-gendered, character-like robots, children with little knowledge of robots preferring a robot that resembled human teachers, and children with knowledge of robots a small machine-like robot (Obaid et al., 2015).

Seeking to understand the impact of robots on studying, Michaelis and Mutlu found that 10- to 12-year-old children reading 13 pages of a textbook made more scientifically accurate statements afterwards if they read with a socially-adept robot (e.g., expressive speech, nonverbal cues, personal comments) than with a socially neutral robot (Michaelis & Mutlu, 2019). There are no similar studies exploring long-term engagement with robots related to learning tasks.

As the use of technologies becomes more ubiquitous in education and more children use devices that they then bring home, caregiver roles (usually parents) become more important. However, few efforts have tried to incorporate parents in the design of school-related technologies. Wong-Villacres et al. developed guidelines for parental involvement in children's education through technology, including supporting equitable informal spaces, providing more opportunities for parents to connect as a community, and providing reliable, relevant, and consistent sources of information (Wong-Villacres et al., 2017). Others have evaluated parental behavior when parents administer assessments to their children (Du et al., 2020).

Language

Reading and writing are among the most important skills children learn in school. Not surprisingly, they have been the focus of many research projects. The examples below concern reading, writing, and acquisition of sign language and second languages.

Reading

Approaches to help children learn to read have included the use of games (Maldonado & Zekelman, 2019; Namatame et al., 2006; Segers & Verhoeven, 2003, 2005; Sluis et al., 2004; Zurita & Nussbaum, 2004). These games have been delivered through desktops (Namatame et al., 2006), using tangibles (Maldonado & Zekelman, 2019; Sluis et al., 2004), and mobile devices (Zurita & Nussbaum, 2004), with goals including learning Japanese characters (Namatame et al., 2006), Roman alphabet letters (Maldonado & Zekelman, 2019), matching sounds (Sluis et al., 2004), learning vocabulary (Segers & Verhoeven, 2003, 2005), and making words out of syllables (Zurita & Nussbaum, 2004).

Others have looked toward the social side of literacy, and also delved deeper in the brain. Jensen et al. targeted expanding the social side through an ethnographic study to investigate the possibilities for use of tangible embedded systems in libraries for promoting early literacy skills. They approached the study from an embodied cognition perspective. Some of the challenges observed included how to engage parents in reading activities and promote enjoyment of conducting early literacy activities with their children (Jensen et al., 2012). Rhodes and Walsh worked on similar issues with children and parents from families with low-literacy adults. Their recommendations include designing reading technologies for parent-child reading activities that encourage accuracy and comprehension over speed, expressing stories through action and voice, and increased reading independence of children (Rhodes & Walsh, 2016). Building on similar ideas for adults and children reading together, Rvachew et al. conducted a study with 28 low-income children in kindergarten and found that an eBook designed to encourage an interactive reading style by the adult and that made an emphasis on comprehension enabled higher gains in children's emergent literacy knowledge than a paper-based alternative (Rvachew et al., 2017).

Others have tried to have children read together with some type of agent. Yadollahi worked with robots, but with children in the role of experts and robots making mistakes (Yadollahi et al., 2018). Xu and Warschauer studied the use of voice-based interactions. They found that commercial voice-based literacy applications for children typically do not leverage conversation technologies for interactive learning and provide limited feedback, among other shortcomings (Y. Xu & Warschauer, 2020a). In the process of designing a conversational agent to read with children, they found that they should be personalized to children's individual practices and needs (Y. Xu & Warschauer, 2020b). Kory Westlund et al. used robots that could point at picture cards and found young children could learn vocabulary from them as well as they could from humans (Kory Westlund et al., 2017).

Cognitive aspects present challenges for children with dyslexia, who require specific types of supports when learning to read. Fan et al. developed a tangible system called *PhonoBlocks* based on theories of causes and interventions for children with dyslexia (Fan et al., 2016). Children who used the system made gains in reading and spelling for both trained and new words (Fan et al., 2017).

Looking more deeply into the brain, Huang et al. developed *FOCUS,* a reading system that used electroencephalography to track children's engagement in reading. When children lost focus while reading, an activity was projected onto the book that prompted children to focus on the topic to re-engage them with the text (J. Huang et al., 2014).

Regardless of the method of reading and related technology, finding stories to read that are engaging to children can motivate them to do more reading. Rubegni and Landoni found that 9- to 12-year-old children experiencing multimedia stories preferred those with interesting plots, well-defined characters, and the creative use of multimedia elements. In addition, social influence (i.e., children telling others about interesting stories) also motivated further reading (Rubegni & Landoni, 2016).

Other reading user interfaces not geared at learning how to read are discussed in Chapter 9 under *Annotating and interacting with digital content*.

Writing

Support for writing has come in three forms: helping children with the motor skills necessary for handwriting, with spelling, and with higher-level writing concepts, such as rhetoric skills.

Janet Read's group at the University of Central Lancashire conducted extensive research on handwriting. They began by using handwriting recognition software to study the type of errors that occur and how children deal with them, as well as children's mental models of how handwriting recognition software works (J. C. Read et al., 2002, 2003). From there, they moved on to design and develop novel writing interfaces with 6- and 7-year-old children (J. C. Read et al., 2004). In follow up work, Kano et al. studied the use of phrase sets for the evaluation of handwriting recognition (standard phrases are typically used to compare handwriting recognition systems) and found that a phrase set with phrases taken from children's books yielded similar results to a standard phrase set without issues of unsuitable, difficult, or regionalized language (Kano et al., 2006). An additional study by Read found that 7- and 8-year-old children generally produced more text during a free writing activity when using handwriting recognition on a tablet computer than when typing on a QWERTY keyboard (J. C. Read, 2007). Using paper and pencil was superior to both computer technologies. More recent work on handwriting has used robots, which children can hold while the robots make letter shapes. There are indications that children who are learning to write are able to recognize writing mistakes made by the robots (Chandra et al., 2017) and that activities with robots could help children learn letter shapes more quickly (Asselborn et al., 2018).

A common challenge for children during their primary school years is spelling. Many applications, including word processors, provide spelling suggestions when children misspell a word. Downs et al. found that children ages 6 to 12 tended to select the first alternative presented to them. They then conducted a study where they found that using synthesized speech in conjunction with spelling suggestions resulted in a greater likelihood of selecting the correct suggestion (Downs et al., 2020).

Others have explored spelling through constructionist approaches. Sysoev et al. developed *SpeechBlocks*, an app that enabled children to rearrange letter combinations to generate words that would then be pronounced by the system (Sysoev et al., 2017). Makini et al. approached the motivational aspects of spelling through an app in which children could generate animated objects by spelling them and explore related words (Makini et al., 2020).

In terms of supporting higher-level writing concepts, an example of research came from Stringer et al., who developed a system to teach rhetoric skills to 11-year-old children. The system helped children construct arguments by helping them organize material they gathered from digital sources using physical tags (Stringer et al., 2004). With a similar goal and setup, Heslop et al. designed a system intended for children to collaborate in persuasive writing activities on a large tabletop display. The system, intended for teenage users, provided them with evidence from which to build the writing. They could then create paragraphs and associate evidence with each paragraph. Some of the writing tasks could be conducted in parallel (e.g., adding evidence to a paragraph), while others needed agreement from the group (e.g., creating a new paragraph) (Heslop et al., 2013).

Sign language

Learning sign language usually involves heavy use of video (Quinto-Pozos, 2011). Computers can provide novel ways of obtaining video to make learning more accessible to children. For example, Huang et al. developed an interactive tool for teaching American Sign Language to deaf preschool children which used a teddy bear with an embedded LCD screen and an RFID reader. Children could interact with it by showing the bear a card with an RFID tag that corresponded to a word and seeing a video of how to sign that word (K. Huang et al., 2008).

Second languages

Within child-computer interaction, much of the literature on teaching second languages comes from research conducted in low-income regions of the world. One line of research came from Matthew Kam and collaborators, who conducted their research in a rural region of India with the goal of teaching English as a second language. To better approach the local children, they researched traditional games to use as the basis of educational games (Kam et al., 2009). They implemented these educational games in low-cost cell phones (A. Kumar et al., 2010). Through a 26-week evaluation of the games, they found that word learning dropped dramatically after eight weeks, although slow and steady gains continued throughout the rest of the study. Kumar et al. continued this line of work with games that used speech recognition. The idea was to enable children to practice vocalizing words as they learned English. In a study with 21 participants ages 9 to 13 years old, enabling vocalization in games (as opposed to only having the children listen to the words) led to greater language gains (A. Kumar et al., 2012).

Fan and Antle, also working in a low-income region (in this case in China), leveraged an augmented reality version of *PhonoBlocks*, an app originally designed for children with dyslexia, for children to learn the alphabetic principle of English. The system combined physical letters with a tablet app that provided feedback through colors, phonological sounds, and 3D animations. They found that the color cues were useful, the 3D animations were motivating, and that children were able to manipulate physical letters without a problem (Fan & Antle, 2020).

An unusual situation is when indigenous languages are in danger of extinction and the only way to keep them alive is to teach them to children. Matos developed software to teach an unusual language, Silbo Gomero, the whistled language of the islanders from La Gomera (Matos, 2017).

Other efforts have been decidedly on the other end of the cost spectrum, with one project using autonomous social robots and emotion recognition to support language learning for preschool children (Gordon et al., 2016).

Mathematics

Mathematics has long been a focus of educational software, with some researchers in child-computer interaction focusing on novel ways of approaching activities to help children learn mathematical concepts. Below are a few examples including educational video games, support for early math activities, helping children understand fractions, the use of cross-platform approaches, as well as museum- and classroom-based exploration of data and mathematical concepts.

A common way of making mathematics more interesting to children is to incorporate it into video games. In such situations it may be useful to be able to predict who is likely to benefit from playing such video games. Deater-Deckard et al. studied the use of a tablet-based math game with ninety-seven 11- to 14-year-old children. They found that observed, but not self-reported, engagement was a predictor for learning the content, and that children with more video gaming experience were less likely to be engaged in the long term, which negatively affected their learning outcomes (Deater-Deckard et al., 2014). Others have studied how to manipulate difficulty in these games (Maertens et al., 2014) and how different avatar representations of children yield different outcomes in terms of fatigue, engagement, and stress (Lee-Cultura et al., 2020). There have also been efforts at developing games that can be more easily incorporated into classrooms, such as games that use augmented reality with math textbooks (J. Li et al., 2020).

An alternative way of motivating children to learn math can be the use of stories. Ruan et al., for example, found that presenting mathematical concepts to 3- to 5-year-old children using stories kept them better engaged in their learning activities than presenting the same concepts without stories, while adding help through a chatbot improved children's learning outcomes (Ruan et al., 2020).

Another way to engage children, at least in the short term, is through screen-based agents. Ogan et al. presented a study on a system for learning mathematics that involved an anthropomorphic agent that children had to teach how to solve mathematical problems. The participants were twelve children who were in seventh to tenth grade who interacted with the agent for part of two 90-minute sessions. The study found that if students used language suggesting a partnership with the agent, they were more likely to learn (Ogan, Finkelstein, et al., 2012). A study of similar software use in low-income regions in Latin America found that children used the systems in similar ways to children in high-income regions, except that they were more likely to collaborate with peers (Ogan, Walker, et al., 2012).

Kosmyna et al. proposed using commercial electroencephalography headbands to enable children to control a robot prior to participating in mathematical activities, with results of a pilot study suggesting possible gains in persistence and enjoyment (Kosmyna et al., 2020).

An example of support for early mathematics skills came from Khandelwal and Mazalek who developed an interactive tabletop environment where preschool children could engage in activities by manipulating objects on a table. The activities enabled learning about numbers, patterns, sorting and classification, geometric shapes, and measurement (Khandelwal & Mazalek, 2007). Beşevli et al. worked on similar concepts with 3- to 5-year-old children, making use of a combination of storytelling, tangible objects, and projections to help children learn about numerical magnitudes (Beşevli et al., 2019). A method that is often used in early mathematical development is concreteness fading, which teaches abstract concepts by moving children from physical, to pictorial, to abstract representations. Suh et al. presented a survey of the use of this method and its implications for interaction design (Suh et al., 2020).

In elementary school, a math topic that can often be difficult for children is fractions. One line of research in this area has been pursued by K.K. Lamberty through *DigiQuilt*, a system children can use to design quilts while learning about fractions. In a study discussed in Lamberty, the children became so engaged with designing quilts that they traded their designs on printed cards and sold them on magnets for fundraisers. The social aspects of the activities around the tool boosted its impact in the classroom (Lamberty, 2008). Given the success of the initial system, Lamberty et al. studied augmenting their work on *DigiQuilt* by adding a large display where children could see each other's designs. Having a large display helped students learn about their classmates' designs, which in turn influenced their own designs, gave them ideas, and boosted their motivation to put something together for a larger audience (Lamberty et al., 2011).

Another approach to fractions has involved the use of the body to better understand ratios. In the *Mathematical Imagery Trainer*, children had to position their hands at heights that corresponded to the desired ratio presented by the system. It provided feedback through screen colors to help children know when they were wrong, almost right, and right (Abrahamson & Trninic, 2011; Howison et al., 2011). In doing so, the system brought together interactions through perception and physical action (Abrahamson, 2013, 2014; Charoenying et al., 2012). Further research from Abrahamson's group studied scaffolding approaches for children to understand basic algebra concepts (Chase & Abrahamson, 2015). In a somewhat similar line exploring trigonometry, Davis et al. used haptic feedback (Davis et al., 2017).

Statistics education is a topic that has not received much attention from the child-computer interaction community. Lee et al. developed a novel approach to introduce statistical concepts to fifth-grade children. They would wear *Fitbit* trackers during the day and then explore data from the trackers to study statistical concepts (V. R. Lee et al., 2015).

A common current practice involves the development of educational software together with educational television. This is often referred to as cross-platform or transmedia learning. The rationale for this approach is that it provides the ability to match content to the most appropriate medium, providing multiple points of entry (based on preferred media), and enabling repetition and reinforcement (Fisch, 2013). Studies during the past few years, summarized below, provide evidence of the advantages of this approach.

Fisch et al. presented an eight-week study with 672 fourth-grade children comparing the different patterns of use of media from *Cyberchase,* a mathematics-oriented television show. Researchers assigned children to one of four conditions: DVD only, web only, DVD + web, DVD + web + outreach activity, or no exposure. The greatest gains in mathematics problem solving were for the DVD + web condition. Some of the implications from this study included the importance of the stories to provide explanations and scaffolding, and of complementary media (web apps for children to practice what they learn when watching television) (Fisch et al., 2011).

In another study involving television-related media, McCarthy et al. studied the use of web and mobile mathematics games with 90 parent/child dyads who were mostly part of low-income families. The games were from *PBS Kids*, the child-oriented branch of public television in the United States. When compared to a control group, the children who played the games showed a statistically significant increase in standardized mathematics scores (McCarthy et al., 2013).

Sometimes mathematical concepts are presented in museums, although it can be difficult to design ways for children to interact with them. Roberts et al. (2014) presented their experience developing a museum exhibit to enable children to visually explore data from the United States Census. To make it work in a museum environment, the researchers used body-based interactions to control the visualization, with users stepping on tiles to navigate between years (Roberts et al., 2014).

There has also been research on environments to support problem solving in mathematics. Moher (2009) presented the design and evaluation of *Who's Who*, an application for use in a classroom to learn about multivariate systems and interference. The system made use of a classroom projector to display a grid of circles, where the circles could be orange or blue. The goal of the activity was for the whole class to achieve a target pattern for the circles. Each child got to control one circle through a handheld device, but they did not know which one it was. The children needed to work together to understand who controlled what circle in order to achieve the desired pattern (Moher, 2009).

Natural sciences

Research on interactive technologies for children to learn about the natural sciences has included work on tools to support the scientific inquiry process, simulations to help children understand scientific concepts and processes, and to a lesser degree visualizations of scientific data.

Supporting scientific inquiry

Science education for children is slowly shifting from children primarily learning science facts to experiencing scientific inquiry processes. Interactive technologies to support the scientific inquiry process usually provide scaffolds that walk children through the stages of scientific inquiry. These stages may include conducting background research, stating hypotheses, planning an observation, collecting and tagging data from an observation, analyzing the data, and reaching conclusions.

One of the most basic ways of supporting scientific inquiry is to support collaborative data collection in the field. This has become significantly easier with the greater availability of mobile devices. An early example came through the *Tangible Flags* system by Chipman and colleagues. Through this system, children could tag an item of interest with a physical flag and annotate it using a tablet computer. Other children who encountered the flag could scan it in order to see the annotation on a tablet computer, and modify it. In a study with eighteen 5- and 6-year-old children, the researchers found increased awareness, more shared experiences, and longer participation times than when using a paper-based annotation system (Chipman et al., 2011). Alakärppä et al. pursued a similar idea using augmented reality, but in this case, elements in nature, such as plants, were pre-identified, and children could learn information about them through the system (Alakärppä et al., 2017).

Others focused on particular types of data. Wyeth and MacColl, developed a mobile app called *Noise Detectives*, which enabled children to record sound levels throughout their schools. It combined the use of a mobile device to measure decibels and paper maps to make annotations (Wyeth & MacColl, 2010). Another effort dedicated to a particular type of data came from Kim et al., who developed visual interfaces for children to monitor indoor air quality (S. Kim et al., 2020).

Some systems designed for scientific inquiry of specific types of data have involved technical innovations. An example is *SharedPhys*, which combined body-sensing technologies with visualizations to conduct scientific inquiries about the human body (Kang et al., 2016). *SmartIR* made use of an infrared camera on a smartphone, and used augmented reality to enable a clearer understanding of laboratory experiments, with a focus on thermodynamics (S. Jiang et al., 2020).

Other tools provide support for several stages of scientific inquiry. One example is *Zydeco,* a mobile app developed by Chris Quintana's group at the University of Michigan (Cahill et al., 2011; Kuhn et al., 2011). *Zydeco* supports scientific inquiry by guiding children through asking questions, capturing evidence, and making claims supported by evidence. The original intent of the app was to bridge museum and school contexts. In an evaluation of such use, middle school students had more active sociocultural engagement when using *Zydeco* than when using worksheets (Kuhn et al., 2011). Kuhn et al. studied the use of *Zydeco* in the classroom with 54 students aged 11 to 13. They found that students made heavy use of a *Zydeco* feature that enabled them to annotate pictures and audio by tagging them. An overwhelming majority of the tags were accurate (over 90 percent). However, the children did not often use the tags for searching, instead preferring to browse through the images available to them (Kuhn et al., 2012).

Another exploration of *Zydeco* came from Clegg et al., who compared it to *StoryKit,* a multimedia storytelling mobile app, to record science activities related to cooking. In an exploratory study with nine 9- to 13-year-old children, all the children preferred using *StoryKit,* although they found *Zydeco* useful for introductory and semi-structured investigations. Lessons learned from the study included the importance of providing children the ability to draw to enable personal expression and supporting the use of tags for organizing and visualizing data, while providing these supports only when needed (Clegg et al., 2012).

Inspired in part by the research comparing *Zydeco*, *StoryKit,* and other tools, such as *SINQ* (Ahn et al., 2012), Yip et al. studied the use of social media in science education through the development of an app called *ScienceKit.* The app enables children to document their scientific inquiry activities, post questions, hypotheses, and ideas, and playfully express themselves. It adds more social elements than *Zydeco* and *StoryKit* while providing structure and the opportunity for children to easily express ideas (J. Yip et al., 2014). *Science Everywhere* built on the experiences with *ScienceKit* to leverage social media use to engage with science concepts outside of learning environments (Mills et al., 2018). Following a more structured approach to science activities outside learning environments, Chu et al. developed a smartwatch app, *ScienceStories*, to prompt elementary school children to reflect on science topics as they went about daily activities (Chu et al., 2019).

Earlier related work included research by Sharples et al. on providing children handheld computers to capture and organize content such as notes and photographs (Sharples et al., 2002). The *Ambient Wood* project also provided children with handheld devices to explore a digitally enhanced woodland environment where they could capture data and later organize it to understand environmental processes (Randell et al., 2004; Rogers et al., 2004). In similar work, Bouvin et al. developed a system that allowed children to explore a city and annotate locations with information, then share these annotations with classmates (Bouvin et al., 2005).

Other researchers have focused on supporting inquiry through computers available in computer labs at schools. For example, Shimoda et al. discussed the design of an online learning environment called *Web of Inquiry* intended to be used in the classroom for science learning. The system, designed primarily for children aged 10 to 13, included tools for brainstorming ideas, tracking progress in a scientific inquiry process, conducting discussions, reporting on work, entering data, charting data, and obtaining advice (Shimoda et al., 2013).

Simulations

Computers can provide children with learning opportunities not otherwise available by taking them to places and situations they would otherwise not be able to experience. That is the motivation behind providing children with access to simulations. The following are examples of this line of research, going from virtual environments, to classroom-based simulations, socially-oriented simulations, and interactive simulations with tangible user interfaces.

Virtual environments, typically delivered through traditional computers, can enable children to explore spaces that are too far away, too dangerous, too small, or too large for them to reach or comprehend. They can involve play (Roussou, 2004), exploration of physical environments through the control of avatars (Göttel, 2007), and immersive environments (Moher et al., 1999).

Simulations can also be scaled in time and space to fit a classroom and its activities. This has been the preferred approach of Tom Moher's group (Moher, 2006). These simulations, called embedded phenomena, work by providing children with displays to monitor phenomena. The simulations run continuously over weeks or months, enabling children to monitor events and conduct scientific inquiries in a convenient setting. One implementation came in the form of *WallCology*, a simulation of an ecosystem that exists virtually on the walls of a classroom, with different types of creatures coexisting, some living on pipes, others on walls (Moher et al., 2008). Malcolm et al. studied the results of two deployments of *WallCology* in fourth- and seventh-grade classrooms. During the deployments, children were able to understand habitat preferences and life stages (Malcolm et al., 2008). The older students were also able to understand the basics of population estimates. Novellis and Moher continued working on embedded phenomena with *AquaRoom,* which simulated subterranean water flow. The simulation enabled students to conduct a dye-tracing method to identify the directional flow of subterranean water flows. A pilot study suggested the approach helped students investigate the simulated phenomena collaboratively and learn basic hydrology concepts (Novellis & Moher, 2011).

Some simulations are more interactive, even involving programming. For example, Sengupta and Voss Farris presented *ViMAP*, a visual programming language and modeling platform for learning kinematics. The learning goal for the system was to help children better understand motion as a continuous process of change. *ViMAP* enabled children to program agents in a simulated environment. The system included a programming area, a simulation area, and a measurement area. In a study with third- and fourth-grade students, the authors found improved test scores in post-tests on topics such as constant acceleration and generating speed-time graphs (Sengupta & Farris, 2012).

Others have followed on these examples, leveraging computing to enable children to create or manipulate computational models of scientific phenomena. Guo et al. worked on *Frog Pond*, an interactive learning environment designed for seventh-grade students, in which children interacted primarily through programming. The system enabled children to simulate evolutionary processes (Guo et al., 2016). Also targeting seventh-grade students, Saba et al. developed *Much.Matter.in.Motion*, a system that enabled children to build computational models of complex chemical systems involving gases (Saba et al., 2020). Pursuing more general-purpose approaches to enable children to build computational models of scientific phenomena, Aslan et al. presented the concept of phenomenological programming (Aslan et al., 2020).

Social simulations

Handheld computers can add mobility and collaborative aspects to simulations. An early example came from Danesh et al. who designed *Geney*, an app that enabled children to “mate” beings with different characteristics to learn about genetics (Danesh et al., 2001).

Handhelds can also support simulations in larger spaces, including playgrounds. For example, Facer et al. developed a game that simulated the African savannah, its resources, and animals to teach children about lion behavior. In this simulation, children played the part of lions that had to work together in order to survive. The savannah environment was mapped onto a school playground, and each child carried a GPS-enabled handheld that provided them with options based on their location (Benford et al., 2005; Facer et al., 2004).

Tangible user interfaces often make it easier for groups of children to interact with a simulation. This approach has worked well for simulations of sustainability and environmental issues and typically involves manipulating aspects of a simulation through tangibles and seeing the outcomes on a screen.

For example, Zhang et al. presented an interactive board application in which children "consumed" different types of energy by manipulating cards and cubes, and saw the impact of their choices on a game world represented on a screen (Zhang et al., 2010). Antle et al. had a similar approach with *Towards Utopia* and its successor *Youtopia,* which enabled children to learn about land use planning and sustainable development. The system included tangible stamps, each corresponding to a type of land use, an information station that children could use to learn about each type of land use, and an interactive tabletop showing a map where children could use stamps to indicate desired land use. After making land use decisions, children could see the outcome on the environment. The game enabled children to learn about tradeoffs between economic development and natural resources based on the emergent dialogue model. While it was not possible in the game to meet all of the population's needs while not polluting, it was possible to come close. In an evaluation of *Towards Utopia* with 30 children aged 7 to 10, there were clear learning gains based on a questionnaire on sustainability (A. N. Antle et al., 2011, 2014).

Tangible setups can also come in the form of semi-robotic characters. Fleck et al. developed *Teegi*, which had a head, torso, arms, and legs, and was designed to enable children to learn about the relationship between brain activity and the functions of the human body. Moving different parts of *Teegi's* body caused its head to light up in patterns corresponding to the areas of the human brain that would be activated if people were to move the same body part (Fleck et al., 2018).

Museum exhibits are an ideal location for interactive simulations supporting multiple participants. D'Angelo et al. developed such a system called *Fishing with Friends* for use in an aquarium. The system enabled users to learn about the environmental impact of fishing practices by controlling fishing ships on a large multitouch tabletop (D'Angelo et al., 2015).

It is also possible to enable social aspects in simulations by using embodied interactions. For example, Keifert et al. developed a play environment that enabled 6- to 8-year-old children to learn about states of matter while playing in an open school space. Children could manipulate states of matter through their collective motion and get feedback on it through a large, projected visualization (Keifert et al., 2017).

Visualizations

Data are an important part of learning about science, and visualizations are a useful way to explore data and spaces. Within the child-computer interaction field there has been research on ecologically-themed, scale, and time visualizations.

In the realm of ecological and sustainability visualizations, Desjardins and Wakkary completed an exploratory study on children's views of sustainability in the home. Through the study, they gained a better understanding of possible designs of eco-visualizations for children. The 9- to 13-year-old children in the study had sophisticated understandings of sustainability, and elaborate ideas for visualizations, suggesting children could be key users of such technology (Desjardins & Wakkary, 2011).

Also thinking about sustainable themes, Ryokai et al. developed *EnergyBugs,* wearable devices worn on a wrist or ankle that could be used to harvest energy through body motions. Their intent was to enable reflection about how energy is produced and how to best use it. The system also involved a station where children could visualize how much energy they had collected and use it for activities including mixing colors (Ryokai et al., 2014).

Mora Guiard and Pares (2014) veered away from data visualization and into scientific visualization when they designed a museum exhibit for children to explore concepts of nanoscale by visualizing different sizes. The setup used motion-based, full-body interactions. A comparison with desktop-only interactions showed better outcomes with the full-body interactions (Mora-Guiard & Pares, 2014).

Sometimes visualizations can help young children understand simple concepts. Hayashi et al. presented *TimeBlocks*, a set of objects intended to help children aged 3 to 5 with understanding time, especially when there is a need to negotiate time with parents. Their cubes lit up and could be set to each last a span of minutes. The cubes could also be stacked to show children how long they had to participate in an activity. They provided children feedback by fading in turn as time went by (Hayashi et al., 2012). Müller et al. also studied visualizations of time for young children, in their case making use of an ambient light display (H. Müller et al., 2016).

There are also simple concepts related to spatial ability. Lee et al. developed a game to help children gain spatial ability skills, wherein one child would place an item in a Lego village and another would have to find it based on a surface level picture of its location (T. Lee et al., 2016).

Embodied experiences

A novel way for children to learn science is to experience it through their bodies. Malinverni et al. conducted a study to learn whether use of a large (3 by 4 meter) interactive slide led to learning gains compared to the use of a computer for a game concerning the concept of gravity. The researchers assessed learning gains through pre- and post-test questionnaires on topics of density, mass, volume and other physics concepts. The results pointed at greater gains for children who used the interactive slide, which directly exposed them, through their bodies, to the concept of gravity (Malinverni et al., 2012).

Computing

The ubiquity of computing in society has prompted a novel set of efforts on computing literacy that do not include programming, which was covered in Chapter 7. This line of work aims to help children learn about concepts related to computing that may have an impact in their lives, such as privacy and security, networking, sensors, and artificial intelligence.

Computing is impacting children's lives early on and it is important for them to be aware of key issues that may affect their safe use of technology, in particular once they become more independent. With this challenge in mind, Maqsood et al. developed *A Day in the Life of Jos*, an online game to introduce 11- to 13-year-old children to topics such as cyberbullying, online tracking, privacy, sharing online, and authentication through interactive scenarios (Maqsood et al., 2018). With similar goals, DiPaola et al. presented their experience organizing a workshop with 19 middle-school children (typically 10-to 15-years-old) to enable children to gain an understanding of design agendas in popular technologies by analyzing stakeholder-value pairs for a popular app (DiPaola et al., 2020). Focusing on sensors, Lechelt et al. developed an exploratory activity for 9- to 11-year-old children to critically think about personal and environmental data sensors (Lechelt et al., 2020). Others have attempted to take these educational activities to children as young as preschool, with Williams et al. presenting their work on *PopBots*, which enabled preschoolers to train and interact with social robots to learn about artificial intelligence topics, such as supervised machine learning (R. Williams et al., 2019).

Other topics are more closely related to computational thinking. For example, Brooks and Sjöberg presented their experience with an activity they conducted with 9- to 10-year-old children where the children learned computational thinking concepts, such as procedural skills, as they put together stop-motion animation videos (Brooks & Sjöberg, 2020). Working with the same age group, Trory et al. developed a system to teach about network routing. The system made use of the concept of concreteness fading, moving students from seeing concrete implications of network connections and costs through toys, to superimposing a routing table, to showing a routing table by itself (Trory et al., 2018).

Social, interactive exhibits in museums

Museums are a long-valued venue for children's learning and increasingly feature interactive exhibits designed for children that go beyond exploring data. In this section we discuss research intended to apply to a wide range of museum exhibit experiences, not focused on a particular topic.

One line of research, from Panagiotis Apostolellis, first highlighted the importance of scaffolds to enable better learning outcomes in museums, which could be achieved through museum guides introducing interactive exhibits, or through features in the exhibits themselves (Apostolellis & Bowman, 2015). Later, he studied options for levels of involvement in exhibits when large groups of children (e.g., from schools) visit and not all of them can directly interact with exhibits, finding that even some involvement in the exhibits led to better engagement and in some cases greater retention of information (Apostolellis et al., 2018; Apostolellis & Bowman, 2016).

Lyons et al. studied how to best support complex social interactions with the goal of learning when designing multitouch tabletop exhibits. A key lesson they learned in building one such exhibit was the importance of making the materials, actions, states, and outcomes clearly visible not just to those interacting with the exhibit, but also to those acting as an audience (Lyons et al., 2015).

In a similar vein, Horn et al. compared the use of multitouch tabletops to the use of tabletops that use tangible technologies. In other words, does having objects that children and family members can pick up and move add something that touch alone does not provide? In their investigation they found that tangible systems provided advantages in terms of attracting and engaging children and family members, but that once interactions began, both types of user interface were equally able to support collaborative interaction (Horn et al., 2020).

Beheshti et al. chose to explore a novel technology, haptic feedback displays, to understand how they impacted the effectiveness of a museum exhibit designed for parent-child pairs to use. They found that there were slight learning advantages when using the haptic feedback displays compared to a regular touchscreen (Beheshti et al., 2019).

Other topics

Executive function

Executive function (EF), as covered in Chapter 2, refers to a set of skills, including self-regulation, necessary for goal-oriented activities. These skills have been associated with better school performance, but little research has been conducted on supporting the development of these skills with technologies. The most common approach in the literature is to use games to train specific EF skills. This is the case, for example, with the *Cookie Monster Challenge*, a tablet game preschool children can co-play with parents (Sobel et al., 2019). Another example is *BrainQuest*, designed for 10- to 11-year-old children to train into multitasking (S. Gray et al., 2015). Pantoja et al. followed a different approach with *StoryCarnival* (Pantoja et al., 2017, 2019a), in which they provide technology supports for preschool children to help them overcome barriers to social play in the style of the *Tools of the*

Mind curriculum (Bodrova & Leong, 2007), which is focused on broadly enhancing executive function skills.

Humanities

In the realm of history, one example that is related to the scientific inquiry tools described earlier was the work by Costabile et al. on *Explore!*, a mobile learning system designed for children who visit archeological sites. The primary target age was 10- to 12-year-old children. The system was set up as a scavenger hunt where children played in small groups to discover hidden secrets in archeological sites, marking these sites on a map. As children progressed through the game, they received rewards through their mobile devices, such as three-dimensional reconstructions of the sites they visited (Costabile et al., 2008).

Other efforts have thought to engage children in civic processes. For example, Peacock et al. worked with 9- to 10-year-old children to help them participate in an urban design project that was seeking community input, using technologies to facilitate data gathering and discussion before children provided their feedback to authorities (Peacock et al., 2018). Lamarra et al. focused on designing location-based mobile games through workshops with 9- to 15-year-old children with the goal of raising awareness of civic and social issues, such as pollution and waste management (Lamarra et al., 2019). Civic and social issues sometimes result in new laws. The *Law in Children's Lives* project aimed to design a game for 7- to 11-year-old children to elicit children's knowledge about laws (Law et al., 2016).

Sex education

With more research in child-computer interaction shifting to focus on the teenage years, researchers are beginning to delve into new areas for technology development, such as sex education. Wood et al. worked on a multiplayer mobile game using prompts with the goal of sparking conversations about sex and sexuality (M. Wood et al., 2017). Meanwhile, Liang et al. gathered requirements for online sex education resources for transgender and gender-diverse youth by interacting with youth aged 15 to 21 (Liang et al., 2020).

Music and sound

Computers can also help children learn about music. Zhou et al. presented *MOGCLASS*, a collaborative music environment intended to help children learn music, including composition, listening, and performance. The system made use of smartphones to provide user interfaces for the teacher and children, as well as a computer connected to a speaker. Through this system, the teacher could configure lessons and manage student interfaces. Children could play virtual instruments through the interfaces. The rationale for this was that it made it easier to put theory into practice without having to learn the intricacies of playing a physical instrument. The system enabled children to practice solo (only listening to their instrument), or to play together. The researchers compared *MOGCLASS* to the use of recorders (the wind instruments) with 8- and 9-year-old children, with findings suggesting greater interest in using *MOGCLASS* as well as greater perceived ease of use (Zhou et al., 2011).

Focused specifically on learning to play piano, Xiao et al. developed *Andantino*. They designed the system to follow a specific method of music pedagogy and supported it by projecting light silhouettes to appear to walk on the keyboard and keys that needed to be played (Xiao et al., 2016).

Focusing on children’s awareness of sound, Carlson et al. explored the use of sound-based tangible-toys with 3- to 4-year-old children. The exploration included toys to record ambient sound, sounds that the children made, and shaking sounds (K. Carlson et al., 2019).

Summary

Learning and educational technologies are among the most active areas of research within child-computer interaction. This research has produced guidelines for approaches to the design of learning technologies, as well as guidelines for specific genres of learning technologies, and for the use of specific types of user interfaces (e.g., tangibles) in educational applications for children.

Another area for research has been with respect to strategies to make computers available in schools. Work in this area has included the use of multiple input devices with one computer, low-cost laptops such as those from the One Laptop Per Child Foundation, and multitouch tabletop displays.

The most popular topics for educational software within the child-computer interaction community mirror those that are most prominent in discussions about education. Hence, most of the research has been in support of reading, writing, mathematics, and science education. Most applications geared at reading aim to make it fun through games. In terms of writing, there have been efforts to support children learning the motor skills necessary for handwriting, as well as research on helping children become organized writers of essays. There are also examples of projects aimed at teaching children second languages.

In terms of mathematics, there are two areas where most of the research within the child-computer interaction community has focused. One is in the teaching of fractions, which is often a difficult concept for children to understand. The other area has been what is often referred to as cross-platform or transmedia learning, where educational programming in traditional media is complemented with games or other activities available on the web or through mobile devices.

When it comes to supporting science learning, there are three areas that have captured most of the research. The first is tools to support children conducting scientific inquiries. These often involve structure and support for conducting background research, stating hypotheses, planning an observation, collecting and tagging data from an observation, analyzing the data, and reaching conclusions. The second is simulations, which include virtual environments, simulations scaled in time and space to fit in a classroom, simulations over a larger space (e.g., a playground) experienced through handhelds, and simulations where children use tangibles to manipulate a system and see the result of their manipulations on a display. The third is visualizations that can be used to see different scales, or to better understand everyday scientific phenomena.

In the above-mentioned examples, learning is largely supported through exploration, creation, and play, oftentimes with social aspects. However, some types of learning may be better supported by behaviorist approaches that make a greater emphasis on practice and reinforcement (e.g., learning to play a musical instrument). Behaviorist approaches are also used to prepare children for standardized tests and help them practice basic mathematical concepts. This is one of the spaces where intelligent agents are used. This is a controversial approach where human-like characters attempt to engage children in activities, taking the place of a teacher or peer. While there is some positive evidence of greater motivation for children in the short term, there is a lack of evidence for long-term positive effects.

The research summarized in this chapter paints a picture of how interactive technologies are increasingly playing a role in children's learning. This is likely to continue to be one of the major foci of research in child-computer interaction, with many challenges remaining, from how to best integrate computers in schools, to how to optimally leverage computers to teach basic skills.

Chapter 11
Health, Disability, and Marginalization

With editorial feedback from Narcís Parés, Universitat Pompeu Fabra, Barcelona

Computers are increasingly used in healthcare, to support children with disabilities, and marginalized children. This chapter discusses research in the child-computer interaction community with a focus on these areas. It includes a review of work on promoting physical activity, teaching healthy habits, helping children with specific medical conditions and marginalized children, and supporting children with various disabilities or who are neurodiverse, such as children diagnosed with autism spectrum conditions or motor impairments.

Promoting healthy lifestyles

Computers and technology have been criticized for enticing children into more sedentary lifestyles that get in the way of healthy behaviors (Sisson et al., 2009). Many researchers have responded by working on technologies that support active lifestyles. As part of a literature review on these technologies, Ma et al. identified design requirement topics including physical activity, social aspects, learning, gameplay experiences, and physical and social constraints (Ma et al., 2019). Below we discuss examples of these, classified based on whether they support indoor or outdoor activities, or other healthy habits.

Indoor physical activities

Computer-supported indoor physical activity significantly increased with the release of gaming platforms supporting body motion as input, such as the *Nintendo Wii* and *Microsoft Kinect*, although the popularity and support for these games began to erode in the latter half of the 2010s. Early investigations on this type of approach were discussed in the child-computer interaction community, for example by Hoysniemi, who found through an international survey that teenagers playing a popular dance game were motivated to exercise, lost weight, improved muscle strength, acquired a better sense of rhythm, slept better, and improved their body image (Hoysniemi, 2006).

Another line of research has come from Narcís Parés's team at Universitat Pompeu Fabra in Barcelona. They have studied the design of a large interactive slide for use in big indoor spaces (e.g., school gymnasiums). Soler-Adillon et al. presented the interactive slide project to the child-computer interaction community. The system, as described, used a very large inflatable slide (3 by 4 meters), a projector, and a camera. The setup enabled children to play interactive games. The games developed often involved sliding down at the right time to intercept a moving object projected onto the slide. The games could be played in groups and encouraged physical activity, since in order to continue playing, children had to climb back up to the top of the slide (Soler-Adillon et al., 2009). The researchers have deployed the interactive slide during exhibitions and conferences, including the Interaction Design and Children (IDC) 2010 conference in Barcelona. Landry et al. examined how interactive slide games could be designed to promote specific types of movement. They designed a game to promote specific types of movement combinations and found that 11- and 12-year-old children who participated in a study were more likely to make those movement combinations when playing the game than when playing another game also designed for the slide (Landry et al., 2013). In a second study, Landry and Parés provided evidence that by controlling a game system variable they called *Interaction Tempo*, they could control and modulate the amount of physical activity by children (Landry & Pares, 2014).

Others have looked for ways of improving physical education classes in schools. For example, Ma et al. presented the design of *Shuttlezap*, which uses audio to augment the experience of playing games with a shuttlecock or birdie (the projectile used in badminton). They found that audio augmentation based on the use of an accelerometer embedded in the *Shuttlezap* helped 13- to 14-year-old children feel more relaxed while playing compared to playing with no audio augmentation (Ma et al., 2018).

Thinking of hospitalized children, Boon et al. developed the concept of *Playscapes* with the goal of bringing three qualities they identified in outdoor play (bodily play, dispersed play, and free play) indoors. Their implementation of the concept was in the form of two games designed for children undergoing cancer treatment in hospitals (Boon et al., 2016).

Outdoor physical activities

A related area of research has been in the design of computer-augmented outdoor physical activities. These have included intelligent or augmented playgrounds and digitally augmented outdoor games. In addition, there has been research on what activities and skills these playgrounds and games should support, the use of sensors to assess playground safety, and the types of messages that are more likely to encourage teenagers to engage in physical activity. An emerging area is the use of technologies to support play in natural settings (e.g., parks).

One form of the computer-augmented outdoors play has been in playgrounds. Pioneering work in this area came from Lund et al., who designed *Playware* technology, which used sensors, actuators, hardware, and software in building blocks used for playgrounds (Lund et al., 2005). This work led others to consider how this type of playground could be designed. For example, Sturm et al. focused on goals such as social interaction, simplicity, challenges, goals, and feedback (Sturm et al., 2008). Seitinger was concerned with how these playgrounds could be used to develop spatial competence, including taking multiple perspectives, zooming in and out, estimating distances, experiencing motion, and encountering rich visual clues. She argued for exertion and ubiquitous user interfaces that could support these aspects of spatial cognitive development (Seitinger, 2009).

In a similar space, Tieben et al. presented on their experience with public, playful installations for teenagers. Their motivation was to help teenagers engage socially in physically active play. They built a prototype with a set of “wiggle benches” that could be wiggled by the teenagers, who could also make other benches vibrate and control a light setup in the playground space. They explored different games and setups based on the intelligent playground’s capabilities. While the installations enabled social, active play, it was difficult for the teenagers to understand the rules of each game as many of them tried to interact in the playground at the same time in an uncoordinated manner (Tieben et al., 2014).

Another approach to promoting outdoor physical activities is digitally augmented outdoor games, usually implemented through handheld devices. An example came from Magielse and Markopoulos, who presented the design of an outdoor group game called *HeartBeat*, which used a handheld device that could track one’s heartbeat through a wireless heart rate sensor. The game was a version of capture the flag, with one player randomly assigned the flag, which they could virtually pass to others in their team by bringing the handheld devices together. Players in the opposing team could tag those defending the flag with their devices, forcing them to join the attacking team. Heart rate was used such that if a player’s heart rate exceeded 100 beats per minute, the opposing team’s devices would start beeping, alerting the player with the elevated heart rate of their positions. The researchers evaluated the game with a group of 11- to 13-year-old children (Magielse & Markopoulos, 2009). Avontuur et al. continued this line of work through enabling children to modify the rules of games such as capture the flag or tag with handheld devices and an application called *GameBaker* (Avontuur et al., 2014). An analogous approach enabled children to use *Scratch* to make games for a similar handheld device (Ofer et al., 2019). Dylan et al. explored the use of more elaborate devices to support children's free play in playgrounds. They found the devices they prototyped could be used to motivate play and extend existing forms of play, with children taking ownership over games. They also found challenges related to disagreements between children (Dylan et al., 2020).

Computers can also play a positive role with respect to safety in playgrounds. Ouchi et al., for example, used sensors to better understand child behavior on a rock-climbing wall in order to design safer future walls. Their approach could be further extended to better model children's behavior on playgrounds to design safer playground equipment and anticipate accidents before they occur (Ouchi et al., 2010).

A more recent trend related to physical activity is support for outdoor activities in natural settings (e.g., parks). Cumbo and Iversen worked with nine 7- to 11-year-old children to identify design possibilities in this space. They included providing children the ability to record and communicate about important places (e.g., a tree), negotiate play boundaries with adults, gather data about the place (e.g., scientific readings), crowdsource suitable places to play, and provide guides to appropriate play activities by location (Cumbo & Iversen, 2020). Kawas et al. explored one of these design possibilities, gathering data through an app called *NatureCollections* that enabled children to build, curate, and share photo collections of species and plants. Through a deployment with 9- to 12-year-old children, they found that children in a group that used *NatureCollections* increased their interest in plants and species and had more conversations about them when compared to children using a standard photography app (Kawas, Kuhn, et al., 2020).

Sometimes the challenge is to get children motivated to participate in physical activities. Arteaga et al. found that personality traits affected teenagers' views on physical activity and apps used to encourage it. They were able to identify motivational phrases that worked across different personalities (e.g., “You have been working really hard! Great job!”). They also learned about the app characteristics that the teenagers who participated in the research preferred: social or competitive, outdoor, simple to learn, and novel (Arteaga et al., 2010).

Healthy habits

Traditionally, caregivers have had the responsibility of teaching children about healthy habits. Some researchers have looked at ways of adding computers into the mix, with research on motivating proper hygiene and nutrition as well as avoiding hazardous substances.

In terms of proper hygiene, the focus has been on helping children learn about dental hygiene and encouraging healthy teeth brushing habits. Andrews et al. used digitally tagged foods to simulate tooth decay and help preschool children understand the importance of brushing teeth (Andrews et al., 2003). Also thinking about dental health, Chang et al. shared the design of a system to help 5-year-old children brush their teeth. The system gamified brushing, telling children where to brush next and providing feedback on where they still needed to brush, based on information gleaned from a camera. The feedback included both a visual map of teeth and the use of musical notes. During a one-week study, the authors found reduced amounts of plaque on children’s teeth, although there was no control group as part of the study (Y.-C. Chang et al., 2008).

A topic related to dental health that has gained notoriety due to the obesity epidemic is nutrition. To help children learn about nutrition, De Carolis and Rossano developed a set of pedagogical agents that worked together to present information to children as a team. For their example, the agents were characters from the well-known children’s television series *The Smurfs*. The system enabled content to be delivered by the team of agents, each with its own role, personality, and communication style (De Carolis &

Rossano, 2009).

Joi et al. focused on gamifying healthy eating through an interactive setup that involved a food tray, a spoon, and a smartphone app. The setup encouraged healthy eating and verbal interactions with parents about food as part of an educational game (Joi et al., 2016).

Another challenge related to nutrition is helping children critically analyze advertising for foods, as commercial children's programming often includes advertising for foods high in sugar. Grimes Parker et al. studied the use of an online health forum to help children address this challenge. The researchers studied the use of the forum by 28 middle-school children (roughly ages 12 to 15) for four days, for approximately 15 to 30 minutes each day. They found that since the children were co-located as part of the exercise, this led to offline discussions that enhanced the impact of the forum. At the same time, Grimes Parker et al. suggested that future systems provide additional structure to help children engage in deeper critical reflection (Parker et al., 2013).

Another goal of this research is to help children avoid hazardous substances in the home. Fails et al. developed a physical interactive environment to teach children about these substances. They compared the environment with a similar desktop application and found the physical environment provided some qualitative advantages for children, though pre- and post-tests suggested that children learned about hazardous materials in both environments (Fails et al., 2005).

Addressing health conditions

Regretfully, some children suffer from health conditions that can bring significant challenges to their lives. To address these challenges, researchers have worked on videogames, educational technologies, and technologies to help with monitoring conditions, communication, and social support.

Thinking broadly about one possible role for computers, Høiseth et al. presented ideas for guidelines for the design of healthcare games for toddlers ages 1 to 3 undergoing medical treatment. These ideas were based on workshops with healthcare professionals and human-computer interaction experts. The guidelines included providing treatment-relevant play activities, supporting family-centered activities, using stories to tell toddlers that they share the same treatment with someone else (e.g., a character in a story), using repetitive elements, using rewards, mixing reality and fantasy, and providing practical and informative information (Høiseth et al., 2013). In subsequent research, Høiseth and Van Mechelen reviewed technologies designed to improve children's well-being connected to issues related to being overweight. They recommended that future efforts consider educational and peer support approaches in addition to games, evaluating outcomes through longitudinal studies, and co-learning about these issues with children as opposed to focusing on changing children's behavior (Høiseth & Van Mechelen, 2017).

Another need related to specific health conditions is to educate children about them. An example of work in this area came from Leong and Horn, who developed interactive education materials to help children learn about sickle cell disease while in waiting areas in clinics. Their system included an augmented reality tablet app used together with physical props to help children better understand hemoglobin structure and how it affects blood flow. The augmented reality setup enabled children to feel with their hands the difference between hemoglobin structures while understanding how they turned out that way (Leong & Horn, 2014). Also aiming to educate children about a specific medical condition, McEwan et al. developed *Puppy Island*, a game designed to help 3- to 5-year-old children learn about cystic fibrosis (McEwan et al., 2020).

Some health conditions require regular monitoring in order to obtain positive health outcomes. This can sometimes cause conflict between children and parents. Toscos et al. studied the challenges with these situations in the realm of diabetes management. Through interviews with children aged 8 to 17, they found issues such as frustration with data collection (e.g., with blood glucose meters), fear among parents of losing control over their children's diabetes management, metabolic changes brought about by puberty, feelings of shame associated with the challenges in managing diabetes, and lack of trust from parents in the late teenage years combined with the teenagers' desire for independence (Toscos et al., 2012). In similar research with teenagers diagnosed with Type 1 diabetes, Webster et al. found that children's self-management behaviors sometimes conflicted with the desire to fit in with peers, and that creating peer-support networks may be valuable to counter these challenges (Webster et al., 2015). Shin and Holtz worked with 10- to 16-year-old children also diagnosed with Type 1 diabetes, focusing on self-management challenges while at school and the possible role of technologies in this setting. Some of the concerns they identified included the inconvenience of using monitoring devices during certain school activities, such as sports, and the need for age-appropriate education on managing personal health information (J. Y. Shin & Holtz, 2020). To address some of these self-management challenges teenagers face, Kyfonidis and Lennon developed a set of tangible toys to help educate children younger than 9 about Type 1 diabetes. The setup enabled children to understand the relationship between food, exercise, insulin, and blood glucose monitoring (Kyfonidis & Lennon, 2019).

Some health monitoring equipment can result in stressful experiences, in particular for young children. Vonach et al. developed *MediCubes*, a set of tangible devices that could be used to measure temperature, pulse and oxygen saturation, and lung function. In an evaluation with 5- to 12-year-old children, the researchers found that their devices could produce reliable measurements while providing stress-free experiences to children and their parents (Vonach et al., 2016).

Another time when children need support is when they are hospitalized, which can lead to stressful and uncomfortable situations. Examples of research in this area include the work of Weiss et al., who used videoconferencing to link hospitalized children with their classrooms (Weiss et al., 2001). Another approach was presented by Bers et al., who provided pediatric patients in a dialysis unit with access to a virtual community through a graphical user interface. The idea behind the research was for children to receive support from their community while they were in a situation where they could not physically interact with others as they received treatment. The tool helped children communicate with others and escape thinking about dialysis (Bers et al., 2001). The same research group had previously worked on text-based storytelling technologies for children in a cardiology unit (Bers et al., 1998).

Immersive games can be useful to provide children with a distraction during painful or uncomfortable procedures. Gold et al., for example, were able to reduce children's pain perception and anxiety during intravenous placement by giving children a head-mounted display through which they could play a game (Gold et al., 2006).

Another approach is to use virtual reality to reduce anxiety and stress involved with a procedure by having children go through the steps of information, observation, modeling, and exposure, prior to experiencing the procedure. Liszio and Masuch experimented with this approach to help 8- to 15-year-old children who needed to go through MRI exams (Liszio & Masuch, 2017).

Mental health

Some children have mental health conditions that can negatively affect their development. Researchers have been working on using technology to augment existing options for diagnoses and therapies to make them more effective.

On the diagnostic side, Roffo et al. presented their research on automating the administration and analysis of psychiatric tests.

Their specific focus was the Manchester Child Attachment Story Task, which is used to assess potential challenges related to children's attachment (or lack thereof) to caregivers. Their automated system matched the outcomes selected by experts in more than 80% of cases (Roffo et al., 2019).

In terms of augmenting existing therapies, Benveniste et al. chose to work on group music therapy. They developed a system for children with behavioral disorders (e.g., hyperactivity, borderline personality disorder, instability). The therapy's aim was to help children better adapt to social settings. The system used *Nintendo Wii* controllers (*Wiimotes*) to enable children to control specific instruments to make music together. The researchers conducted two field studies with 7- to 12-year-old children. They found the therapy sessions helped with mediation, enabling the children to connect the activity with their personal histories and feelings (Benveniste et al., 2009).

Sandtrays are another approach commonly used in therapy with children. Hancock et al. developed a virtual version of sandtray therapy for a tabletop display. In sandtray therapy, patients interact with figurines to create scenes as they are observed by a therapist. The researchers worked with three therapists to develop a prototype that was deemed by the therapists as sufficient to gain similar insights as they would gain with the original setup. The rationale for having a virtual version was to have easy access to a wider variety and greater number of objects for constructing scenes (Hancock et al., 2010).

Cognitive behavioral therapy (CBT) is broadly used to address a variety of mental health concerns for both children and adults. Ferri et al. presented initial ideas for *Games 4 Therapy*, an initiative intending to explore the design of apps to support CBT (Ferri et al., 2016).

Other forms of supporting children have emerged out of new bio- and neuro-feedback technologies. For example, van Rooij et al.

explored the use of sensors to detect breathing patterns and used them to design a virtual reality game to motivate breathing patterns that help reduce anxiety (van Rooij et al., 2016). Antle et al. used an electroencephalography headset as input to games intended to help children self-regulate anxiety. Surveys of parents and teachers suggested that the games helped children self-regulate anxiety when not using them (A. N. Antle et al., 2019).

Sometimes computers can make it easier to keep track of information that is useful in therapy sessions. Matthews and Doherty took advantage of this opportunity through a mobile phone system that enabled teenagers to track their symptoms to later review them with a therapist. In an evaluation with 10 users, use of the tracking tool led to increased adherence to therapy (Matthews & Doherty, 2011).

Communication

Communication with health professionals and other patients can be an important component in helping children manage health conditions and obtain support. In this area, there has been research in helping children better communicate with clinicians, health professionals, and other children with the same condition.

Hourcade et al. presented a study on the use of tablets to enhance the communication between children with chronic headaches and medical professionals. Their idea was to help children better describe their headaches so that accurate diagnoses could be achieved. The study compared different forms of using drawing to communicate about headaches, the research itself building upon evidence that drawing on paper provided advantages in communication over standard communication methods. The study provided evidence that a zoomable drawing app on a tablet enabled children to provide about 50 percent more descriptors about their headaches than drawing on paper (Hourcade, Driessnack, et al., 2012).

Also researching ways of improving communications with health professionals, Bonner et al. reported on observational research with child life specialists, who provide assistance to children in hospitals. These included observation of two mobile applications. They observed both collaborative (with active collaboration) and co-present activities (where there was co-presence but no direct collaboration). One of the main challenges in designing for these environments was the frequent interruptions when other medical professionals needed access to the children (Bonner et al., 2012).

There have also been many efforts to provide social support, especially for children with rare or socially stigmatized conditions. Lindberg et al. investigated design patterns to provide social support for children recovering from rare diseases. Their idea was to provide children with peer support when the numbers of children affected are low enough that local support communities are not available. The patterns, developed through a series of workshops, included helpful play, posing open questions, switching between single and multiple actors, managing degrees of privacy, and sharing (Lindberg et al., 2014). Also aiming to provide peer support, Bhattacharya et al. tested the use of asynchronous remote communities to help teenagers manage stress. In their experience, while teenagers appreciated the flexibility of the system, they did not use it often (Bhattacharya et al., 2019). In earlier work, Duveskog et al. developed an interactive platform for young people (mostly secondary school students) to discuss their experiences with HIV and AIDS in Tanzania. Pilot studies suggested the stories were easy to understand, easy to relate to, captivating, stimulated questions, and were entertaining and engaging (Duveskog et al., 2009).

Children with disabilities

During the past decade, there has been a significant increase in the amount of research on technologies designed for children with disabilities, including neurodiverse children. The sections below present research on technologies for children with various forms of impairments (i.e., visual, hearing and speech, motor, cognitive), as well as children with multiple impairments, children diagnosed with autism, and other developmental disabilities. Challenges that occur when designing these technologies include difficulty assessing their impact and conducting participatory design activities. The former is related to the relatively low numbers of children with specific conditions or disabilities, as well as the high amount of variability in their needs, abilities, and preferences. The latter is related to communication challenges.

Visual impairments

Research on technologies for children with visual impairments has increased significantly during the latter half of the 2010s. Most of the early efforts were by Jaime Sánchez and his research group. For example, Sánchez and Flores designed and developed audio-based learning environments for and with children with visual impairments ages 6 to 15. The environments were geared at developing working memory and mathematics skills. An experiment showed particularly positive results in mathematics learning (Sánchez & Flores, 2003). Sánchez and Sáenz conducted similar work, adding three-dimensional sound in the context of solving problems related to geography and culture (Sánchez & Sáenz, 2005). This was based on earlier work on experiencing interactive stories using three-dimensional sound (Lumbreras & Sánchez, 1999). With the related goal of helping children with a wide range of visual impairments experience maps, Brulé et al. designed *MapSense*, which also enabled children to play and collaborate, and adult caretakers to customize the experience (Brulé et al., 2016). A continuation of this line of work focused on the design of a wrist-worn device to enable children to record audio cues during field trips. The device was intended to elevate the role of sound and hearing as part of geography education (Brulé & Bailly, 2018). Freeman et al. also proposed an approach with a wrist-worn device to enable children to be more fully integrated in school activities by providing greater awareness of proximity to people, places, and activities (Freeman et al., 2017).

Other researchers have followed multisensory approaches too. McElligott and van Leeuwen collaborated with blind children in the design of tools and toys combining tactile and audio interactions. They followed the philosophy of designing for children's abilities instead of around their disabilities (McElligott & van Leeuwen, 2004). Raisamo et al. designed and developed a game for children with visual impairments that used haptic feedback from an off-the-shelf gamepad. The game was designed to help children in memory tasks (Raisamo et al., 2007).

An area of recent interest is programming environments that support children with visual impairments (Kane et al., 2018; L. R. Milne, 2017; L. R. Milne & Ladner, 2018; Morrison et al., 2020; Pires et al., 2020; Thieme et al., 2017). We cover these efforts in chapter 7.

Metatla and his research group have been focusing on supporting children with mixed visual abilities, as children with visual impairments increasingly attend mainstream schools. An example of his work is the design of an educational game involving robots designed for children with mixed visual abilities. In designing the game they noted key processes to support including negotiating and executing shared goals, symmetry of actions and knowledge, explicit and implicit learning, and division of labor (Metatla, Bardot, et al., 2020).

Hearing and speech impairments

Research on technologies for children with speech impairments has focused primarily on facilitating children's participation in therapy and learning. To evaluate prototypes, some researchers have taken advantage of the Wizard of Oz technique, where children think they are interacting directly with a computer, but instead a human is interpreting their actions and interacting with the machine. Bälter et al. used a Wizard of Oz technique to test the interface to a computer-based speech training system designed for children in need of speech therapy. The technique helped bridge the inaccuracies of the system in the detection of mispronunciations (Bälter et al., 2005). Henderson et al. designed a game for deaf children to learn American Sign Language. They used Wizard of Oz techniques to help with American Sign Language recognition (Henderson et al., 2005). Further development of the game, called *CopyCat*, showed encouraging accuracy levels for word recognition (Brashear et al., 2006).

Video games are indeed an option for encouraging children's practice of speech. Hair et al. presented their work on *Apraxia World,* which enabled children to control an avatar in a virtual world through a video game controller, while acquisition of assets to advance to the next level was tied to speech exercises. An evaluation with 4- to 12-year-old children suggested that children preferred this approach of decoupling avatar control from speech exercises (Hair et al., 2018). Also with the focus of motivating children to practice speech, Hamidi and Baljko presented an original idea. Their system involved "living media"; in this case, a colony of mushrooms that grew according to the amount of speech children practiced (Hamidi & Baljko, 2014).

Using other participatory techniques, Iversen et al. designed and implemented *Stepstone*, an interactive floor application for children with a cochlear implant that tied linguistic learning to body motion and group collaboration (Iversen et al., 2007).

Other work has focused on enabling children with hearing impairments to join others in creative activities involving sound, such as music. The MuSS-Bits++ system, for example, used a vibrotactile device to provide children a sense of rhythm in the context of music classes (Petry et al., 2018).

Please note that Chapter 6 includes a discussion of design methods used with children with disabilities.

Motor impairments

In this area, research has included reflections on how to conduct participatory research with children with motor impairments, and on the design of interactive technologies for drawing, reading instruction, cursor control, exergames (i.e., games involving physical exercise), and music performance.

Hornof discussed his experience designing assistive technologies with children with severe motor impairments. He recommended guidelines for these activities, including accepting communication difficulties, advocating for children’s voices to be heard, using all forms of communication available (including low-tech), interacting with caregivers, learning when to take breaks from activities, joining in other activities in which the children participate, encouraging input by presenting children with multiple alternatives, and working with pairs or multiple children at the same time, especially if they are friends (Hornof, 2009). This was a continuation of Hornof and Cavender’s earlier work on *EyeDraw*, which used eye tracking technology to enable children with severe motor impairments to draw by using their gaze. They proposed a multilayer approach to these types of user interfaces to enable children to easily get started with simple options while avoiding frustration from having too many features available (Hornof & Cavender, 2005).

Also using eye gaze to interact with computers, Sibert et al. developed a system for remedial reading instruction that used eye gaze to trigger auditory prompts (Sibert et al., 2000). Since operating a computer through eye gaze can be both difficult and tiring, Raya et al. studied the design of a system for children with cerebral palsy that could enable them to interact with a computer using a head tracker. They compared the use of different kinds of filters to help address problems with spasms and shaky movements (Raya et al., 2010).

Difficulties interacting with computers and videogame consoles can get in the way of children with motor impairments enjoying videogames. To address this limitation and provide an added benefit of exercise, Hernandez et al. developed a station to support exercise games for children with cerebral palsy. Through the station, children were able to provide input to the game through pedaling and using a standard game controller. Because children with cerebral palsy were not able to pedal smoothly, the researchers added software to smooth the input sent to the gaming console. Through their design, seven of eight children with whom the researchers worked were able to play an exercise game. Their investigation also included details on the challenges and opportunities with handheld game controllers for this population of children. Their lessons for designers of games for this group included simplifying level geometry (to reduce the need for carefully timed actions), simplifying level flow (to reduce the number of decisions that need to be made in a given amount of time), reducing the consequences of mistakes, limiting available actions, removing the need for precise pointing or aiming, making the game state clearly visible, and compensating for differences in players' gross motor skills (Hernandez et al., 2012, 2013). These findings are useful in the context of evidence that children with cerebral palsy tend to be more motivated to exercise and can better exercise when using game-like virtual reality environments than when conducting conventional exercises (Bryanton et al., 2006).

Other technologies that have been explored to motivate children during physical therapy include robots. They are typically used to work as novel coaches, as well as to motivate children to engage in exercises (Malik et al., 2016).

Another activity that children with motor impairments can be excluded from is playing musical instruments. Thinking of this challenge, Meckin and Bryan-Kinns developed *moosikMasheens*. Their system consisted of musical instruments, such as guitars, that were adapted so they could be played electro-mechanically. This adaptation enabled children to play an actual guitar without having to touch it, instead interacting with it through whatever user interface suited their abilities (Meckin & Bryan-Kinns, 2013).

Developmental disabilities

Research on technologies designed for children with developmental disabilities has been increasing since around 2016, whereas few efforts occurred before. Most projects aim to support children with specific developmental disabilities. Note that due to the high volume, research on autism is covered in a separate section.

A few research efforts are intended to generically apply to children with developmental disabilities. One example comes from Virnes et al., who studied the use of educational robots (*Lego Mindstorms* and *Topobo*) to assist children with learning disabilities. They studied the individual needs of children across the following dimensions: expression (i.e., being able to implement their own ideas), exploring while constructing (e.g., exploring capabilities while building), hands-on programming (i.e., computer-based vs. tangible), two-directional communication through imagination (how children communicated with the robots), need for instructions (balancing power and flexibility with ease of programming), and need for intervention (how often adults need to be involved) (Virnes et al., 2008). Lin et al. focused on children with developmental delays and their interactions with a game-based visual perception learning system. In a survey of 150 therapists, parents, and other adults in an instructional role, they sought to learn about factors affecting continued use of the system. They learned, not surprisingly, that satisfaction had a positive influence on continued use and that it was most affected by perceived playfulness, followed by perceived usability and usefulness (Lin et al., 2017).

Children diagnosed with attention-deficit/hyperactivity disorder (ADHD) tend to have trouble paying attention, controlling impulsive behaviors, and may be perceived as being overly active when compared to peers (CDC, 2020c). About 1 in 10 children in the United States has been diagnosed with ADHD (CDC, 2020d). Sonne and colleagues worked on a system called *MOBERO* to help families with children diagnosed with ADHD establish family routines. They found the system helped children become more independent with bedtime routines (Sonne, Marshall, et al., 2016; Sonne, Müller, et al., 2016). Working with 24 children aged 10 to 13, Cibrian et al. explored the possible use of smartwatches to support children's self-regulation through participatory design sessions (Cibrian et al., 2020). To lower the cost and increase the accessibility of ADHD diagnoses, Jiang et al. developed *WeDa*, a system that used sensors and three-dimensional interactive devices for diagnostic purposes (X. Jiang et al., 2020).

There are also examples of research focusing specifically on children with Down syndrome, who typically have learning and motor impairments. Brandão et al. described a game for children between the ages of 3 and 7. The game, called *JECRIPE*, was meant to stimulate imitation, perception, fine motor skills, hand-eye coordination, and receptive and expressive verbal language, through tasks involving imitating dance moves, singing along, popping virtual bubbles, and matching colors (Brandão, Brandão, et al., 2010). Also working with children with Down syndrome, Ortega-Tudela and Gomez-Ariza used multimedia tools to teach basic mathematical concepts and found that the children learned better with the game when compared to conducting similar tasks using pencil and paper (Ortega-Tudela & Gómez-Ariza, 2006).

Mandryk et al. developed an approach to provide neurofeedback training for children with Fetal Alcohol Spectrum Disorder (FASD) to help them with self-regulation. The approach used texture-based graphical overlays on games to obscure the screen if children moved away from a desired physiological state. In an evaluation with 16 children between the ages of 8 and 17, the researchers found that the children were better able to self-regulate in the latter sessions of game playing than in the earlier sessions, indicating their improvements in self-regulation through this approach (Mandryk et al., 2013). In similar research, Jessup Schneider et al. found that games for children with FASD should have a low cost of failure, enable taking breaks, show progression, and enable cooperative play (Schneider et al., 2020).

Other work has focused on conditions that have received less attention. For example, Alissa Antle's group developed tangible systems for children with dyslexia to learn spelling, with multiple successful evaluations (E. S. Cramer et al., 2016; Fan et al., 2016, 2017). Sometimes unique designs are necessary for children with very specific disabilities. Robinson et al. provide an example of the design of technology for one boy with severe developmental disabilities due to brain damage (Robinson et al., 2020).

Multiple impairments

Research on technologies for children with multiple impairments has involved investigations of novel user interfaces, social games, social interactions around media, and facilitating face-to-face communication.

In terms of novel user interfaces, Lathan and Malley worked on child-robot interaction for children with a variety of disabilities. Their goal was to help children develop motor skills, speech, and language. They designed the robots so they could be controlled by almost any part of the body, or even through voice (Lathan & Malley, 2001). Kourakli et al. also used body-based interactions in their research using the *Kinems* suite of educational games for children with a variety of impairments, combining motor, cognitive, and academic goals (Kourakli et al., 2017). Also looking at interfaces for diverse impairments, Baloian et al. studied the similarities and differences in technologies that map real world experiences into virtual environments for both blind and deaf children (Baloian et al., 2002).

One of the main challenges for children with multiple impairments can be in communicating and participating in social activities. Ibrahim et al. studied how five 6- to 9-year-old children with severe speech and motor impairments used augmentative and alternative communication (AAC) technologies, which typically consist of digitized picture dictionaries enabling children to select visual items, which are then synthesized into speech. They found that

AAC devices often were not a good match for children's preferred ways of using their bodies to communicate, placed limits on children's control over their communications, and were difficult to adapt to specific social situations (Ibrahim et al., 2018). Looking to promote socialization, Brederode et al. designed and developed a game to bring together 8- to 14-year-old children with and without physical and learning disabilities. The design had the challenge of helping children with disabilities compete with others on an equal footing. The game was also designed to combine cooperation with competition in order to enhance participation and dialogue (Brederode et al., 2005). Another team of researchers on social aspects, Durrant et al., studied ways for children to socialize and express opinions around the topic of digital photography. They conducted five workshops in a mixed-abilities classroom that included children ages 11 to 14 with epilepsy, visual impairment, cerebral palsy, and other disabilities. Based on the workshops, they developed a physical console that enabled children to express their opinions as to how pictures taken of them or by others were displayed in the classroom (Durrant et al., 2013).

Others have focused on helping children with multiple or diverse impairments better communicate with teachers and therapists. Garzotto and Bordogna designed a system called *Talking Paper* that enabled the association of paper-based objects (e.g., a card) with multimedia resources (e.g., sound, image, video) (Garzotto & Bordogna, 2010), later expanding it to any kind of tangible object (Garzotto & Gonella, 2011). The items in the system could be activated in a particular pattern to yield specific outcomes (e.g., telling a story, or learning the steps necessary to accomplish a task). The system provided an alternative to paper-only communication methods and fully computer-based augmentative and alternative communication devices. The intended creators of the experiences would be educators, caregivers, or therapists.

Autism

Starting around 2005, there has been a significant surge in research on interactive technologies designed for children diagnosed with autism, with research in the latter half of the 2010s eclipsing research on technologies for just about any other group of children. This increase in research has gone hand-in-hand with increased rates of autism diagnoses (CDC, 2020b). The majority of these interactive technologies aim to address children's social, communication, and behavioral challenges (CDC, 2020a). Approaches to these technologies have included motion-based games, social activities using multitouch tabletops, tablets, and tangibles, the use of mobile devices to encourage social activities, virtual reality setups, and a variety of applications for supporting communication and building basic skills. There have also been explorations of the potential to use technology for diagnostic purposes (Koirala et al., 2019).

For children with no or very limited verbal communication skills who often have difficulty controlling their bodies, solutions have involved motion-based user interfaces. Parés et al., for example, developed an interactive environment that reacted to utterances, movements, and gestures from children and responded through sound, vibration and visuals (Parés et al., 2005). It was designed to encourage nonrepetitive activities while enabling children to express themselves. Keay-Bright completed similarly inspired work (Bright, 2009). Following the line of work from Narcís Parés at Universitat Pompeu Fabra, Malinveri et al. developed another motion-based game called *Pico's Adventure*, intended for children to play with their parents (Malinverni et al., 2014). Later efforts by this group came from Mora-Guiard et al., who developed *Lands of Fog*, a full-body interaction experience intended to foster social interaction between children diagnosed with autism and their typically developing peers (Mora-Guiard et al., 2016, 2017). While the research projects from the Pompeu Fabra group tend to be implemented in large spaces, Bhattacharya et al. experimented with motion-based interactive activities in classrooms for children diagnosed with autism, finding that the activities encouraged social interactions between children (Bhattacharya et al., 2015). Similarly, Wu et al. developed *SqueeBall*, for use in indoor playgrounds. This system enabled children to interact with it by squeezing colored balls hanging from the ceiling, which could in turn change lights, projections, and produce sounds (Wu et al., 2020).

With some similarities, Bartoli et al. developed ideas for motion-based touchless games for children with autism (Bartoli et al., 2013, 2014). They did so by observing five children diagnosed with autism ages 10 to 12 play Microsoft Kinect games. Through their observations, they created the following guidelines: developing one game per child, supporting evolving needs over time, focusing on one goal at a time (Mohamed et al., 2006), providing clear visual instructions, providing rewards, ensuring repeatability and predictability, minimizing transitions, minimizing the number of visual elements, providing clear feedback through audio, providing dynamic visual stimuli, and making careful use of surprising events to maintain attention and interest. They also listed the goals they had pursued with motion-based games, including increasing gross motor skills, postural stability, coordination, space awareness, and body awareness, as well as promoting perceptual learning and attention skills.

There have been several efforts aimed at improving social skills by engaging children in social activities. Baykal et al. provide an overview of these efforts, finding little geographic diversity, educational settings being the typical location where research takes place, social activities typically involving peers, and technology spanning touch, embodied, and tangible user interfaces. They also find that in a majority of cases, collaboration is a means to an end (usually educational), with a few projects making collaboration a goal in itself, and no clear standards for measuring collaboration (Baykal et al., 2020).

One particular approach has been to use tabletop displays to engage multiple children in activities at the same time. An early example came from Piper et al., who designed a four-player tabletop application that required children to work together (Piper et al., 2006). In a similar tabletop approach, Hendrix et al. worked with shy children, who were given special roles that helped them positively engage with peers (Hendrix et al., 2009). Another example of tabletop use came from a collaboration between Israeli and Italian institutions (Gal et al., 2009, 2016; Giusti et al., 2011), with activities including storytelling and enforced collaboration, similar to Piper et al.'s.

Tablets can also be used to engage children in group activities. Hourcade et al. developed a suite of apps to entice children diagnosed with autism to engage in positive face-to-face interactions. The goal was to help children practice social skills during activities they enjoy. The tablet activities provided a context such that face-to-face interactions, which are often unpleasant for this group of children, became desirable. The suite consisted of a set of simple, flexible apps that could be used in a variety of activities involving creative, collaborative, and expressive endeavors. This setup helped provide combinations of apps and activities that could work for particular sets of children. The apps had very simple user interfaces with little or no use of words to better appeal to a population that can often more easily process visual than verbal information and can easily be distracted by irrelevant visual stimuli. There were no right or wrong ways of doing things in the apps, a design feature which was intended to enable the children to explore the programs, feel free to express themselves, and reduce anxiety. In a study evaluating the apps, the researchers compared them to very similar activities that did not involve computers and found that the app-based activities were associated with more words spoken, more verbal interactions, and greater physical engagement with the activities. In addition, children were more likely to use encouraging comments when using two of the apps (Hourcade, Bullock-Rest, et al., 2012; Hourcade et al., 2013).

Expanding work on tablet use, Holt and Yuill explored the use of activities on two tablets linked by a wireless connection versus one tablet. They found that when children diagnosed with autism participated in activities with either a peer or an adult, there was active other-awareness when using dual tablets, but not when using a single tablet for the specific activity that the authors studied (Holt & Yuill, 2017).

Another technology that has been used for collaboration with children diagnosed with autism is tangible user interfaces. Examples include the work of Farr et al. with *Topobo* and *Playmobil* toys (Farr, Yuill, Harris, et al., 2010; Farr, Yuill, & Raffle, 2010), experiences with robots (Feil-Seifer & Matarić, 2009; Garzotto et al., 2017; Ghorbandaei Pour et al., 2018; Robins et al., 2004), experiences with audio-augmented artifacts (Alessandrini et al., 2016), and for tracking and motivating learning when sorting shapes (K. T. Johnson & Picard, 2017).

Escobedo et al. combined tangibles with augmented reality to teach about *object discrimination* (the correct identification of objects and their characteristics, such as color). Teaching object discrimination can be time consuming and can require a significant amount of note taking. The researchers designed a prototype using tangible devices that could be used to prompt children for specific actions, keep track of successes and failures, and provide feedback and rewards to children. Through an evaluation, they found that children using the tangible setup were more likely to be on task and that teachers spent almost no time taking notes when compared to standard procedures (Escobedo et al., 2014).

Mobile devices are also increasingly used to support people on the autism spectrum in their social interactions. Escobedo et al.'s *MOSOCO* provided children with ideas on who to approach on a playground and how to interact with them. In addition, there are many software apps for both mobile phones and tablets that enable their users to communicate by selecting picture symbols that are then translated into speech for face-to-face communication (Escobedo et al., 2012). These follow the example of earlier augmentative and assistive communication (AAC) devices such as the *DynaVox* but are significantly more affordable. Work from researchers on AAC apps has typically focused on adding personalization and contextualization. It includes Chien et al.'s *iCAN*, which enabled greater customization than many commercial apps (e.g., incorporating images relevant to specific children) (Chien et al., 2015), Wilson et al.'s *MyWord*, which provided children with the ability to customize their own set of personal and contextually relevant words (Wilson et al., 2018), and Shin et al.'s *TalkingBoogie*, which focused on supporting better caregiver communication and collaboration with regard to children's AAC use (D. Shin et al., 2020).

Virtual characters have been used to help children practice face-to-face communication and to communicate with others using the virtual character as a proxy. Examples in this line of research include the work of Tartaro and Cassell (Tartaro & Cassell, 2008) and the *ECHOES* project in the United Kingdom (Porayska-Pomsta et al., 2012). For the latter project, Alcorn et al. reported on what happened when children diagnosed with autism noticed discrepancies in its virtual environment (i.e., events that violated some rule) (Alcorn et al., 2013). These discrepancies were due to software bugs and were therefore unintentional. However, the researchers noted that they often led the 5- to 8-year-old children, who normally had a difficult time communicating, to communicate. The researchers presented evidence from coded videos and suggested this approach could be used intentionally to spark communication. Another recent finding with respect to virtual characters and communication came from Carter et al., who found that children diagnosed with autism improved their social non-verbal behaviors when communicating with a "cartoonized" version of a therapist with exaggerated facial motion (Carter, Hyde, et al., 2016).

More broadly, virtual reality and virtual worlds have become a more common approach to providing new opportunities for developing social skills in the latter half of the 2010s. Examples include the work of Parsons on supporting perspective-taking in mixed-abilities groups (Parsons, 2015), Boyd et al.'s *vrSocial*, which used immersive virtual reality to support proximity regulation (Boyd et al., 2018), Loiacono et al.'s *Social MatchUP*, which aimed to encourage communication through a shared game (Loiacono et al., 2018), and Ringland's study of *Autcraft*, an instance of a *Minecraft* virtual world (Ringland, 2019).

Researchers have also developed many applications targeting traditional desktop and laptop computers, with the aim of improving a variety of skills. These include building vocabulary, vocalizing words, reading human faces, and learning about appropriate forms of communication (Bosseler & Massaro, 2003; Coleman-Martin et al., 2005; Faja et al., 2007; Hailpern et al., 2009; Moore & Calvert, 2000; Whalen et al., 2006). One example is Hailpern et al.'s work on an application to encourage vocalizations. The system enabled children to obtain visual feedback of their vocalizations and used rewards in the form of computer-generated sounds of a length proportional to the correctness of the vocalization (Hailpern et al., 2009). Another recent example geared at learning specific skills comes from Venkatesh et al., who presented a computer-based, early intervention program called *TOBY*. *TOBY* made use of a computer-based implementation of Applied Behavior Analysis therapy. It included exercises to help children build skills, with a hierarchy of these skills put together so that children would master basic skills before attempting to learn more complex ones. *TOBY* also enabled adults to track children's progress and provided detailed instructions for caregivers to conduct exercises (Venkatesh et al., 2013).

Other approaches aim to support children diagnosed with autism by providing better structure to their daily lives. These include the computer-based implementation of visual supports, schedules, and other common tools used in schools (Hayes et al., 2010). For example, Hirano et al. developed *vSked*, a system to help children with the scheduling of classroom activities. Typical ASC-focused classrooms often include a visual schedule for children to anticipate what they will be doing and to help them know what to do next. *vSked* helped teachers and children by enabling individualized schedules (to account for individual needs), allowing children to see what they needed to do next, and making it easier for the whole classroom to be aware of how well they were doing through a large display at the front of the room (Hirano et al., 2010).

Another form of support that has been explored by researchers is in providing help when children display behaviors associated with stress. Zakaria et al. discussed the development of a system that aims to automatically detect behaviors associated with stress through a smartwatch, which was also used to deliver visual cues to help children self-manage their behavior (Zakaria et al., 2016). It is important to note that some of the behaviors targeted by these researchers are considered coping mechanisms by other researchers and members of the autistic community (Kapp et al., 2019).

Mixed-abilities groups

A welcome and very necessary topic of research that has become more popular since the latter half of the 2010s is the design of technologies for groups of children with and without disabilities. Schooling is increasingly integrated for children with disabilities, and their long-term integration in society requires not only that everyone do their part, but that children grow up with positive examples that make shared activities with people with a variety of abilities a typical situation. These inclusive activities are more likely to occur with appropriate, flexible supports while building on children's strengths and interests (Sobel et al., 2015).

Sobel et al. explored two types of supports in the *Incloodle* system, one enforcing cooperation, the other suggesting it through in-app characters. In this experience, enforced cooperation worked better (Sobel et al., 2016). Garzotto et al. explored the use of an interactive room with a variety of sensors and actuators, including projections and speakers. Children could interact with the room in a variety of ways, supporting a wide range of abilities

(Garzotto et al., 2020). Others have focused on robots as a support to bring together children with different abilities. Metatla et al. and Neto et al. both focused on using robots to support inclusive activities for children with and without visual impairments (Metatla, Bardot, et al., 2020; Neto et al., 2020).

Marginalized children

Sometimes children's challenges are related to extreme life situations, such as homelessness. Palzkill Woelfer and Hendry presented their experiences observing the use of technology among young homeless people, aged 13 to 25, who they recruited at a community technology center in Seattle, Washington (USA). They found that the young people's use of computers included elements of their life on the streets (e.g., self-reliance, vulnerability, basic needs) and their participation in the community technology center (e.g., conformity, youth-adult relationships, goals) (Woelfer & Hendry, 2010). More recently, Antle et al. conducted research with Nepalese children living in poverty. They used neurofeedback technology to help the children develop self-regulation skills in order to help them better manage stress (A. N. Antle et al., 2015).

Summary

As computers become ubiquitous in every aspect of our lives, they are also becoming more common in promoting health and helping people with disabilities. For children, we see this trend in technologies that promote healthy habits, such as being physically active and eating well. There are also many examples of technologies used in healthcare, whether they help children learn about a health condition, manage it, communicate about it, or get support from peers. When it comes to neurodiversity and disabilities, technologies can play a role in providing children access to experiences otherwise not available to them, obtaining support for tasks that are difficult, and helping them develop skills and abilities.

In terms of physical activity, there has been research in supporting both indoor and outdoor activities. Indoor activities include augmented indoor playgrounds, with Parés's large interactive slide being a great example. Support for outdoor physical activity includes digitally-augmented interactive playgrounds, as well as games played with handheld devices, and technologies to support play in natural settings.

Work on promoting healthy habits has been mostly geared toward areas that parents often find challenging. These include nutrition (i.e., teaching children about healthy food choices) and learning to brush teeth. There has also been research on helping children learn to identify hazardous substances that may be found in the home.

In terms of helping with health conditions, most of the research has been conducted in supporting children's communication. Within this area, a majority of the work has been with the intention of providing children with social support, whether they have a rare chronic condition and need a support group or they are hospitalized and away from friends and family. There has also been research on better supporting communication between children and health professionals. Other areas of research include the use of games as therapy for specific conditions, technology to teach children about a health condition, and tools to help children monitor their health. A growing area of research on supporting children with mental health conditions has focused on enhancing diagnostic tools and therapies.

Research on technologies to help children with disabilities and who are neurodiverse has increased significantly in the past few years, especially in supporting children diagnosed with autism. For this specific population, research has included technologies to help with social, communication, and verbal skills, as well as executive functions. There has been less attention paid to other disabilities, such as vision, speech, hearing, motor, behavioral, or cognitive impairments, although there are a few examples of research to help each of these populations as well as children who have multiple types of impairments. A welcome development has been the increasing amount of research on supporting inclusive activities that bring together children with and without disabilities.

Together, these areas of research have constituted one of the main areas of growth for the child-computer interaction field in the past few years. The main challenge ahead will be to translate the most successful research into widespread practice.

Chapter 12
Looking Ahead

What are the challenges and opportunities that lie ahead for the field of child-computer interaction? This chapter presents one view on these challenges and opportunities. In terms of challenges, it presents three plagues that could be brought about by technologies: isolating children, quantifying them, and increasing the gaps between high- and low-income populations. This is followed by a discussion of how participatory design and its founding principles may be a cure for these plagues.

The discussion then moves to the available opportunities for the child-computer interaction field to grow and make a bigger difference. These include designing technologies so that they can develop together with children, aiming for universal impacts, demonstrating long-term positive results, and reflecting on how technologies shape children's development.

Challenges: the three plagues

Shneiderman and Plaisant listed their *Ten Plagues of the Information Age* in an appendix to the fourth edition of *Designing the User Interface* (Shneiderman & Plaisant, 2005). In that list, they discussed some of the dangers that the widespread use of computers could bring and is currently bringing upon society. The following discussion, inspired by their writing, is on three plagues that children face as a user population and the cures that our field can provide.

The first plague is for interactions with computers to isolate children. This can happen in cases when computers replace humans in children's lives. The replaced humans can be play partners, family members, or teachers. It can happen when children play games on a computer on their own instead of playing with other children, when computers are used as child sitters, when using a tablet is more interesting than chatting with family during a meal, and when “intelligent” tutors replace teachers. It can also happen when parents and other caregivers are so absorbed with technology that they do not pay as much attention to their children, perhaps even affecting the ability of young children to develop secure attachments. This plague is also a risk in cases where technology makes experiences so personalized that children have increasingly less in common with other children in their lives (e.g., they experience different media or go through school in separate paths). As previously discussed in Chapter 8, computers make it much easier to connect with others who are far away, which can have positive effects in helping children express feelings, get support from others, and connect with distant loved ones. At the same time, there is clearly no substitute for live interactions, as we have learned during COVID-19 pandemic times. Children growing up with fewer face-to-face interactions could have difficulty developing relationships with the people with whom they interact on a daily basis and could suffer from limited social skills in face-to-face interactions. In addition, there is evidence that participation in social interactions facilitates general cognitive functioning (Ybarra et al., 2008).

The second plague is brought by the unabated thirst for personal information by a variety of organizations that seek to quantify and model people, including children. It is facilitated by children’s ubiquitous use of computer technologies that can enable easy collection, storage, and analysis of their data. Note that while some of children’s use of technology is by choice, a lot of other uses are outside their control, particularly in schools that increasingly use technologies to not only keep track of grades and assignments, but also to track student behavior (Andrejevic & Selwyn, 2020; A. J. Lu et al., 2021). While there are laws in some countries designed to protect children’s privacy, they have limited reach, and are far from universal. There are definite potential benefits from delivering personalized experiences to children (e.g., delivering educational content at the right starting point, appealing to children's interests), but the pitfalls involved are significant. The first obvious one is the long-term impact on children's privacy. The second, which is related to our first plague, is that systems that personalize learning could end up leading to children not having meaningful interactions with teachers or even with peers during learning activities. A third potential pitfall is the impact of systems that are incorrect when trying to model and classify children based on their behavior because this could potentially set these children on the wrong track. A fourth issue is that children may feel constantly judged and evaluated through these systems and may associate their self-worth with these systems' models, which typically consider performance in assignments, attendance, and even in-class behavior, but not creativity, kindness, or generosity. A final pitfall is that these systems desensitize children to surveillance of every aspect of their lives, making it less likely they will question it as adults. In other words, children are being trained to accept widespread surveillance for the purpose of assigning them scores based on the goals of organizations with power over them.

The third plague is that the use of computer technologies during childhood will exacerbate inequalities. The digital divide is real and it is likely to increase economic and social gaps. For example, in 2020, the Pew Research Center conducted a survey of parents with children who participated in remote schooling in the United States during the pandemic. They found that 59 percent of parents with lower incomes said their children were likely to face digital obstacles in schoolwork compared to 10 percent of upper income parents (Vogels, 2020). There are projects that are trying to remediate this issue, but even with great publicity and talent, projects such as One Laptop Per Child failed to reach their potential. Even if hardware is made available, there are infrastructure limitations that will need to be taken into account when developing solutions to address lower income populations or children with disabilities. More importantly, any technology that arrives to help disadvantaged children must be relevant to their needs and context. Providing the exact same technology that high-income children who are not disabled access may not be appropriate in many cases.

The way to combat these plagues is to put the needs of all children first when designing technologies, while keeping in mind social and physical contexts. The ideas and values from the UTOPIA project, the pioneering work of Scandinavian researchers and workers that led to the development of participatory design techniques, are relevant as a way of curing these plagues. The UTOPIA project developed three principles to guide the design of technology that are still often cited and interpreted in new contexts: quality of work and products, democracy at work, and emancipation (Ehn, 1988; Iversen et al., 2004).

When referring to quality of work and products, the UTOPIA project made an emphasis on designing technologies to augment user skills rather than replacing them. Following this principle, we should study how we can use computer technology to enhance or encourage face-to-face interactions. For example, instead of replacing teachers, tutors, or peers with computers, we could design technologies that make it easier to interact with them and make the interactions more likely to be constructive and lead to learning experiences. In addition, we can look beyond productivity and think about supporting children's creativity and imagination.

The principle of democracy at work was meant to state that workers should have the right to participate equally in the design of technologies that affect their jobs. If we extend this principle to children, it means that they, their parents, and other stakeholders (e.g., teachers) should also participate in design decisions for technologies designed for their use. We see this reflected in participatory approaches to design that emphasize partnering with children in the design process. These approaches can be one of the cures for the plague of the quantification of children. In general, they make it more likely that there will be outcomes aligned with children's and stakeholders' goals, although they could be improved (Kawas, Yuan, et al., 2020; Van Mechelen et al., 2020). One area in which the research community needs to do more work is in incorporating parents together with their children into the design process .

The principle of emancipation referred to designing technologies so that they can prevent workers from being exploited. This principle can apply to the second plague as well, since massive surveillance for purposes extraneous to children's goals could be considered a form of exploitation. In a broader sense, the principle of emancipation is applicable to the third plague. Can we design technologies in such a way that they will not increase the economic and social gaps between children? Can we provide lower income children and children with disabilities with technologies that will enable them to succeed later in life and be full citizens of the world? Can we design technologies that will make children who face few barriers more aware of the situation of others around the world?

In remembering and following these principles from the UTOPIA project, we can provide children with technologies that will help them grow up to be sociable, creative, responsible, participatory, and globally aware adults.

Opportunities

Where are the opportunities for the child-computer interaction field to deepen its impact and make a greater difference in the future? The sections below discuss areas where more research could be conducted and areas that present challenges for child-computer interaction researchers. Working on these challenges can turn the field of child-computer interaction into a more mature one and will help a broader set of children reap the benefits of computing.

Designing technologies that co-develop with children

Children's development is most advantageous when their surrounding environment supports their growth. Ideally, these should be flexible environments that the child can modify and that can develop with the child. In spite of this ideal, we have largely been designing interactive technologies that are static. While these interactive technologies enable children to modify the environment similar to using a physical tool, they do not change with children. Unlike a static physical tool, however, these technologies are dynamic software, with user interfaces that are able to change as children develop. But how can we make available user interfaces that are the best match for a particular child's cognitive, perceptual, and motor skills, as well as their needs, interests, and preferences?

Instead of following an age-based set of guidelines, a better approach would be to mirror changes in the field of developmental psychology by focusing on how children change in their abilities, needs, and interests. In other words, we need to go from thinking about what children can do when, to thinking about how children change. Doing so would enable us to design technologies such that they could develop with children and provide us with the ability to cater to individual children.

There are three major challenges in developing this new viewpoint. The first challenge is that longitudinal research studies would be needed to understand how children's needs, abilities, and preferences change with respect to technologies. For example, to better understand children's ability to use gestures, we would need to see how the components of these gestures change as children get older. Identifying how these changes occur would help us better address the variability between children and help answer questions as to whether most children follow similar patterns of development, or whether there are diverse paths to achieve a particular ability. Taking a longitudinal view would also help us better understand what experiences, as well as environmental, contextual, physical, and cognitive factors play a role in these development patterns.

A second challenge is in terms of the factors involved. There are a variety of interrelated skills involved in interacting with computers: cognitive, motor, and perceptual. Gaining an understanding of how children change in these skills can be quite complex, with interactions between motor challenges and the perceptual and cognitive complexity of user interfaces (see Figure 7 for an example of how quickly children change in their motor skills). In addition, personal needs and interests, which also change as children grow up, should also be taken into account when thinking about how technologies may develop as children develop.

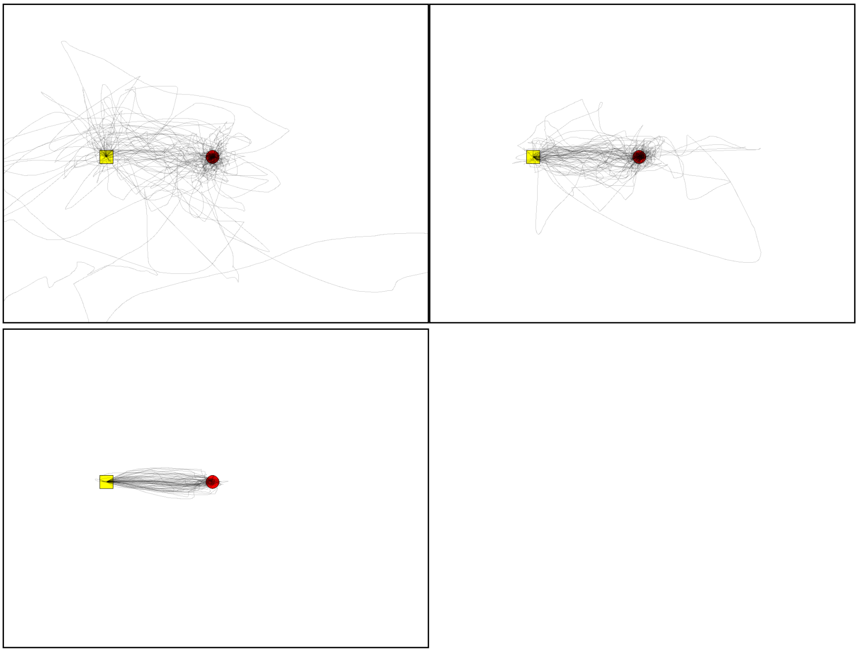

Figure 7. Mouse paths taken to click on a 32-pixel target at a distance of 256 pixels by 4- (top left), 5- (top right), and 18- to 22-(bottom) year-old participants (Hourcade et al. 2004c).

A third challenge is in terms of how to give children control over these technologies so they can change them and customize them as they grow up. How do we provide this ability to change technology while keeping technology generic enough so children can easily get help from adults or peers when necessary? Should there be system suggestions? Can the experience of modifying technologies be more satisfying or beneficial than simply switching to a technology designed for older children?

Aiming for universal impacts

Another area where more research is needed, even though there has been some work, is in terms of ensuring that we design technologies that can make a difference for all children in the world, regardless of their culture, socioeconomic status, or ability. Oftentimes research in child-computer interaction refers to children in general, but in reality, it only applies to some children in the countries where the researchers live. There is a need to broaden target populations across social, economic, cultural, and ability lines.

Perhaps the most important reason to conduct this line of research is the increasing digital divide that can be seen between children in high- and low-income countries and also within each country across socioeconomic lines. This growing gap threatens to increase economic disparities by denying information and computer literacy and preventing children from gaining a wider view of the world. Similar gaps can occur for children with perceptual, motor, or cognitive disabilities.

Working with these populations often brings challenges in terms of hardware and infrastructure. The sad reality is that disadvantaged children will often not have access to the latest and greatest technology. These challenges also pose human-computer interaction design problems that need to be investigated. For example, how should software be designed so that it can gracefully work through spotty Internet connectivity and inconsistent access to electrical power?

Another challenge has to do with the contextualization of user interfaces. Most disadvantaged children come from different cultures and in many cases speak different languages from those spoken by most child-computer interaction researchers. If user interfaces and content do not adjust to local cultures, they may have a very negative impact on the perception of technology and its use. Likewise, technologies need to respond to the everyday realities of children, which may be very different across economic, social, ability, and geographic divides.

Responding to local contexts is also challenging because, in order to be successful, it requires that designers and researchers work with the disadvantaged children, ideally using participatory design techniques. Cultural and most often language barriers provide challenges, along with a potential increase in power dynamic issues which can always be present when adults work with children. It is also unclear whether participatory design techniques that have been developed in Western countries will apply well to other parts of the world. Early results in this area point to the importance of involving local stakeholders in these design activities to help in conducting the activities and with communication between designers and children. Even better results can be obtained if locals have experience in conducting participatory design sessions and can conduct them themselves.

There is also the challenge of considering children who follow development paths that are different from those followed by the majority of children. In order to best support this group of children, we need to design technologies for inclusion from the very beginning, designing for children's strengths, not around their impairments. We need to further consider not just how to design technologies to help children fit in a world designed primarily for people without disabilities, but also work in the opposite direction on technologies that can help those without disabilities see the world from the perspective of those with disabilities.

Demonstrating positive broader impacts

The child-computer interaction community also needs to do a better job of demonstrating that its research outcomes have a positive measurable impact on children's lives. Demonstrating positive results is a necessary step before computers can have a significant positive impact on children's development. While research sometimes shows short-term gains, there are fewer findings on the long-term impact of the technologies being developed. How many studies are out there that follow children using a novel technology for at least a year to understand the impact the technology has on their lives? The lack of this type of study is directly linked to insufficient funding, but at the same time, these are the types of studies that can bring further funding in the future and solidify the reputation of the field.

Relying on short-term studies can be dangerous with novel technologies, providing advantages for novices but often getting in the way as users, including children, become more proficient. Evaluations of software for children should thus follow children as they become experts at using the technology.

Longitudinal studies can also provide information on what factors contribute to success. It may be that the same technology is successful in some classrooms and not others, or with children from a particular socioeconomic group but not others. Longitudinal studies can also prove useful in assessing the societal impact of providing computers and software to children. This is particularly relevant for situations where children are the first members of their family to be introduced to computers. These explorations can also lead to broader knowledge beyond a specific technology, along the lines of the suggestions on intermediate-level knowledge by Barendregt et al. (Barendregt et al., 2017).

Reflecting on how technology shapes children’s cognition

Given the increasing ubiquity of computing devices in children’s lives, we need to reflect on how they are impacting children’s development, and how this affects the type of adults they will become. In particular, we need to carefully think about the ways in which technologies have an impact on cognitive processes. We are already beginning to see an impact, but it is likely to become even greater as children begin to use interactive technologies at younger ages and with greater frequency and as computing technologies are further integrated into cognitive processes.

For example, perception may change through augmented reality technologies that could enable children to perceive much more information about the world around them. Interactive technologies can also be directly tied to memory processes, making it unnecessary to remember phone numbers, addresses, or directions, and perhaps even people's names. To what degree will easily available information impact what children should recall from school? What information is worth memorizing?

The intersection of big data, ubiquitous access to the Internet, and the proliferation of sensors and recording devices also means that children's lives are increasingly being recorded. It is reasonable to expect that children in the next few decades will be able to go back to any day in their lives and find out information on what they were doing that day, or perhaps even videos and detailed records of what they did at school. How will their memories of childhood compare to ours if there is always that record to go back to?

Attention is another cognitive process that is being affected by computers. In particular, there is a sense that mobile devices are often getting in the way of face-to-face interactions (Turkle, 2017). These devices can make high-interest content available, providing instant gratification without having to manage boring, uncomfortable, or less exciting situations. Such high-interest experiences can get in the way of daily interactions with caregivers (Radesky et al., 2014), as mentioned earlier in this chapter, but could also potentially reduce attention spans and the ability to delay gratification. At the same time, there is a growing area of research on biofeedback that is already being used to help children refocus their attention when they are not doing what an adult expects them to do (J. Huang et al., 2014).

Together, all these changes could have a significant impact on the type of adults children grow up to be. The good news is that the child-computer interaction community, including researchers and practitioners, can have an impact. We have the opportunity to design the future of children's experiences with computers. In designing this future, we can also have a direct impact on how children will go about perceiving the world, interacting with others, making decisions, and managing information. The key is to know that as designers of technologies, we have choices and because we have choices, we need to reflect on how the technologies we design will impact children's cognitive processes. More specifically, we can no longer think solely about how a single technology will affect children, but about the role it will play together with all the other technologies in children's ecology.

To help us reflect on the technologies we design, we need to have a vision for the type of humanity we would like to see in the future. As we have seen in the discussion of the three plagues in this chapter and in the chapter on safety issues, interactive technologies can easily lead us to generations of adults who grow up to be anxious, aggressive, isolated, hyper-surveilled, super-consumers in a world of rampant inequality. But we could have an alternative outcome as well: a world with healthy, resourceful people, who find it natural to collaborate with others in creative endeavors, with strong connections to loved ones, and a wide worldview.

Summary

There are challenges and opportunities that can help set a research agenda for the field of child-computer interaction. They are directly tied to what outcomes we would like to see in children: what kind of adults would we like them to grow up to be? In terms of challenges, the three plagues discussed in this chapter were social isolation, quantification, and inequality. The opportunities included designing technologies that develop alongside children, aiming for universal impacts, demonstrating positive results and broader impacts, and reflecting on how computer technologies shape children's cognition.

Ultimately, we have choices in the research and work we do. We need to think carefully about these choices because computers are increasingly playing a ubiquitous role in children's development. What is your vision for the future of humanity?

You can play a role in making it happen.

Appendix A
Development of Specific Processes, Skills, and Abilities

This section provides an overview of how key processes, skills, and attributes develop through childhood. These include perception, memory, problem solving, language, and motor skills.

Perception

Perception involves using the senses to construct an internal representation of space and the body. These abilities are key to making use of technologies, and thus it is crucial for developers of children's technologies to understand how they develop as children grow up.

Vision

Even though the physical development of the eyeball is complete by age 2, children at this age still have difficulty in perceptual tasks, such as distinguishing objects from backgrounds, and tracking moving objects.

One way to measure visual abilities is by assessing visual acuity. Visual acuity is the ability to distinguish details in objects and may be measured in static or dynamic settings. In the static setting, neither the object nor the person looking at it moves. Visual acuity is measured through the familiar Snellen eye chart used in optometrists' offices. Dynamic visual acuity involves perceiving detail in moving objects. Static visual acuity is usually mature by age 10 and undergoes rapid improvements between the ages of 5 and 7 and also between the ages of 9 and 10. Dynamic visual acuity undergoes similar improvements, with a final improvement between ages 11 and 12. Research studies suggest that on average, boys have better static and dynamic visual acuity than girls at all ages (Gallahue, 1989).

Figure-ground perception, or the ability to distinguish objects from a background, improves during childhood. This perceptive ability becomes stable around age 8 to 10, with additional refinement through age 13 and possible continued improvement through age 18 (Gallahue, 1989).

Visual-motor coordination, or the ability to track and make judgments about how to intercept objects, also improves during childhood. Tracking is associated with dynamic visual acuity. By age 5 or 6, children can track objects moving in the horizontal plane. By age 8 or 9, they can track objects moving in an arc. Object interception refers to the ability to estimate an object's future location and use a motor-response to intercept it. For example, a goalkeeper catching a ball in a soccer game would use her object interception skills. This ability also improves throughout childhood as can be seen by observing children play sports that involve object interception skills (Gallahue, 1989).

Perceptual-motor abilities

The perceptual-motor process involves obtaining environmental stimuli through the senses, organizing and integrating information from the senses in the brain, deciding on how to move based on sensory and long-term memory information, transmitting that decision to the muscles, performing the movement, sensing the outcome of the movement, and storing the success or failure of the movement for future reference. The process can be executed in a loop to accomplish complex movements (Gallahue, 1989). Even though motor and cognitive skills were studied separately in the past, there is increasing evidence that they are highly interrelated. Research has found that similar parts of the brain are involved in motor and cognitive skills, and children with cognitive conditions such as attention-deficit/hyperactivity disorder, dyslexia, and autism show deficits in motor tasks (Rao, 2005).

Attention

Attention plays a role in motor skills as well as computer use. Attention is selective, as it involves the ability to filter unwanted stimuli, helping us concentrate on the task at hand. While there is evidence for selective attention from birth, some attention-related skills are not fully developed until children are in elementary school. For example, children are not capable of actively searching for objects until early elementary school (Rao, 2005).

Video games and perceptual abilities

Playing action video games has been associated with better performance in a variety of perceptual tasks including the ability to track multiple objects and distribute visual attention across a field (Dye & Bavelier, 2010; Hubert-Wallander et al., 2011). However, shortcomings in many of the studies conducted on this topic make this only a tentative conclusion (Boot et al., 2011).

Memory

Working memory

Working memory, often referred to as short-term memory, can store information in the short term that can be manipulated. It helps coordinate perception, long-term memory, and action. According to Baddeley, it consists of a central executive, storage for phonological information, and a visuospatial sketchpad. The central executive controls attention as well as the two storage systems. The phonological storage system can keep a limited amount of phonological information that can be manipulated (Baddeley, 2003). Likewise, the visuospatial sketchpad can store and manipulate visual representations (Baddeley, 1998).

Working memory, which for adults holds, on average, seven chunks of information, can typically hold four or five for 5-year-old children, and six for 9-year-old children (Dempster, 1981). This limited working memory capacity affects the complexity of tasks that children can handle. A smaller working memory limits the amount of information children can keep in mind when problem solving as well as the relationships children can establish between pieces of information. Working memory capacity seems to be correlated with information processing speed (Kail, 1997). Experience plays a role in the efficient use of working memory by giving older children and adults strategies that can be used to improve performance, such as chunking information or using external aids (Flavell et al., 2002).

Long-term memory

Explicit memory involves memories that are consciously recalled and includes semantic memory (remembering facts) and episodic memory (remembering events). Implicit memory keeps information that is not consciously stored. It usually involves information about how to complete tasks. It tends to build slowly through repetition (e.g., typing). Older children have advantages in explicit memory tasks, while there are no differences in the performance of older and younger children when forming implicit memories (Rao, 2005).

Children use a number of strategies to store information in long-term memory. Verbal rehearsal is one such strategy that begins to appear in early elementary school. Other strategies include clustering or organizing information, linking concepts through visual images, and selecting the most relevant information to store. The ability to make practical use of these strategies improves during childhood, although in a nonlinear manner that can even include regression (Flavell et al., 2002). Designers of children's technologies can leverage these strategies to aid children's learning.

Symbolic representation

DeLoache and Smith have studied symbolic representation in young children and found that by the time they are 3 years old, most children can understand that a symbol stands for something else, that something can be both an object and a symbol, and that a symbol can represent something in the real world. In order to use symbols, children need to relate the symbol and what it represents, match corresponding elements, and use information from the symbol to infer information about what it represents

(DeLoache & Smith, 1999). Children's development of symbolic representation should be taken into account when designing icons and other visual representations in technologies for children.

Preschoolers can understand and use simple maps, such as a point inside a rectangle to represent the location of an object in a sandbox (Huttenlocher et al., 1999), but still have difficulty understanding the representational nature of maps (e.g., red lines representing roads that are not red) (Liben & Downs, 1991). These developmental aspects are important to know for the increasing number of technologies that make use of geolocation and wayfinding.

Preschoolers are capable of putting together scripts with information on how tasks should be carried out that involve a sequence of actions, locations, and objects. The complexity of scripts children can develop increases during elementary school and is related to narrative thinking abilities (Flavell et al., 2002). The important role of narratives in developing these skills is one of the reasons behind the development of storytelling tools for children.

Many technologies make use of categorizations and hierarchies in order to organize content. Results from studies suggest children begin categorizing objects as early as 14 months of age (Flavell et al., 2002). While preschool children can sometimes make use of hierarchical categorizations, reasoning and problem-solving using hierarchies does not begin to appear until the elementary school years, consistent with Piaget's concrete operations stage (Flavell et al., 2002; Winer, 1980).

Problem solving

Children in elementary school, in Piaget's concrete operations stage, are able to infer facts given certain evidence, even if the facts contradict what they perceive at the time. An example is Piaget's conservation task, where, for example, when water is poured into taller, thinner glasses, preoperational children (preschoolers) usually think that these glasses hold more water than shorter, thicker glasses (Flavell et al., 2002).

Preschoolers are also more likely to concentrate on one aspect of a task and neglect others, while older children can perceive a wider array of information about a task that can enable them to make better decisions and inferences. Likewise, preschoolers are more likely to concentrate on the current state of a task, without paying much attention to what happened previously or anticipating what will occur next. Elementary school children, on the other hand, keep previous events in mind when problem-solving and making decisions, thus obtaining better results (Flavell et al., 2002). These developmental differences suggest that information presented in order to make decisions in technologies should be handled differently for preschoolers when compared to older children.

Unlike older children, preschoolers are typically unable to reverse actions in their heads. In addition, elementary school children can also use the concept of compensation, which applies to the conservation task, where they can determine that a taller glass has the same amount of liquid as a shorter glass because it is thinner (Flavell et al., 2002). Reversibility is important when troubleshooting issues in software and can help in the navigation of user interfaces. Elementary school children (typically ages 6 to 11) are also more likely than preschoolers to use quantitative measures to solve problems or make decisions, while preschoolers are more likely to make qualitative assessments (Flavell et al., 2002). Designers should take these differences into account when giving feedback to children.

Middle school children (typically 12 to 15 years old), in transition between Piaget's concrete and formal operations stages, tend to use empirical evidence when reasoning. They usually base their decisions on evidence they perceive through their senses. On the other hand, teenagers and adults in Piaget's formal operations stage are more likely to reason abstractly, concentrating on the logic of statements and situations. For example, middle school children presented with rigged empirical evidence that violates logic are more likely to believe the empirical evidence than teenagers and adults who would object using logical arguments (Flavell et al., 2002). These differences suggest that children are more likely to suffer from poorly written software and poorly implemented technologies or purposefully deceptive technologies that present illogical or ill-advised recommendations and dialogs.

Middle school children are also more likely to approach problem solving by concentrating on information that is immediately available (mostly through the senses). They solve problems one at a time, within the empirical context of the problem, usually not developing overarching theories. On the other hand, teenagers and adults are more likely to consider all the possible situations and situate the current problem within those. Thus, when problem solving, they will likely consider theories within which a particular problem falls, hypothesize that a particular theory may be the correct one, and deduce from empirical evidence whether this is correct. Furthermore, they are more likely to consider the logical relationship between a series of problems or events and use this information in problem solving (Flavell et al., 2002).

Preschoolers have advanced reasoning abilities when it comes to informal tasks that involve likely facts. For example, preschoolers have the ability to relate new situations to situations previously experienced based on similarities. They are also capable of analogical reasoning, although the performance in these tasks improves over the years as children obtain more knowledge about the world. In addition, they have a basic understanding of causality, or understanding that a particular action can trigger something else to happen (Flavell et al., 2002).

The use of appropriate problem-solving strategies can be sporadic at first, with use becoming more frequent over time. This change involves becoming more proficient in the new strategy as well as suppressing the use of previously used inferior strategies. The use of planning improves as children get older, with children as young as 5 beginning to use planning on a regular basis (Flavell et al., 2002).

Role of memory

Working memory and information processing capacity help problem solving by helping keep in mind goals and facts, as well as providing the ability to evaluate possible strategies and solutions. Experience in problem solving helps develop expertise as children get older. Domain knowledge helps older children retrieve more relevant information about a particular problem as well as recognize the best strategies with which to solve a problem. Familiarity with domain specific information helps free working memory resources, which in turn helps keep more information in mind. This advantage is to the point where expertise tends to override age, with several studies showing that young children can perform at the levels of older children or adults in areas where young children are experts. Expertise, however, is easier to develop for older children and adults. Meta-cognitive capabilities also improve during childhood, providing children a better awareness of their cognitive resources and a wider range of strategies to choose from (Flavell et al., 2002).

The above-mentioned factors can play an enormous role in how children use and perform with technologies. It is very important to document children's background and expertise when conducting experiments and usability studies and make an effort to have them match that of children in the target population for a given technology. These expertise issues may also explain some differences that have been found in experiments being conducted recently when compared to experiments conducted 10 or 20 years ago, when young children's technology ecology was much different.

Social aspects

Older children and adults play an important role in teaching children how to solve problems and their problem-solving approaches are influenced by the problem solving they have been taught or have observed (Flavell et al., 2002). While oftentimes children collaborating with children can provide advantages in problem-solving tasks, there is evidence that sometimes this pairing can also get in the way of children's learning (Rogoff, 1998).

Language

Human brains appear to be best suited for learning languages early in life. An example comes from learning a second language. This is easiest for the youngest children, with this ability decreasing as children get older, with no advantages by the time children reach adolescence (J. S. Johnson & Newport, 1989). The reason why children with less working memory and information processing capacity would learn languages better is still unclear (Flavell et al., 2002). Children learn words at an amazing rate of 800 to 900 words a year between the ages of 1 and 12. However, this rate is not true for every child, as there is a lot of variation in development rates (Biemiller, 2003).

In terms of milestones for children in the United States, by kindergarten most children can identify and name letters, read their name, and read a few simple common words. By third grade, most children can spell common words correctly and read primary-level fiction and nonfiction. By sixth grade, most children read with confidence and can spell a majority of words correctly (Topolovac et al., 1997).

Motor skills

Fine motor skills are necessary for operating input devices, and thus learning about how these skills develop in children is important for understanding the types of issues children may face when using these devices. Much of this research is slowly being replicated through research on children's handwriting abilities with computer devices as well as on children's use of pointing devices, such as the mouse, and touchscreen devices.

Fine motor movements are produced by the smaller muscle groups in the human body, such as those involved in manual activities. Fine motor movements are precise and adaptive. Most research on fine motor skills is focused on manipulation, or the use of the hands. Intrinsic movements involve the use of the fingers to manipulate an object in the hand. Extrinsic movements involve moving the hand and the object it holds (Payne & Isaacs, 2017).

Manipulation

A great increase in intrinsic movements of the hand occurs between ages 3 and 7. During this time, children learn to complete tasks, such as buttoning, that require them to coordinate the action of both hands as well as differentiate the movements of the fingers. Studies on how children complete motor tasks in this age group suggest that they first try a number of approaches for a particular task, eventually settling on the most efficient one. Older children see the speed of their movements increase and the variability in their movements decrease. Reaction times to start movements also decrease (Pehoski, 2005).

One aspect of manipulation that has been extensively studied is children's handwriting. Between the ages of 2 and 6, as the ability to use writing or drawing implements develops, children develop a grip closer to that of adults, moving their hold of implements closer and closer to the tip, thus increasingly using the muscles in their fingers to control movement (Rosenbloom & Horton, 2008). A study found that by age 3, 48 percent of children had an adult grip, and by age 7, 90 percent had an adult grip. The length of the writing instrument and the orientation of the writing surface (vertical vs. horizontal) can have an impact on the maturity of the grip (Yakimishyn & Magill-Evans, 2002). While it is unclear whether pen-based computing will play a significant role in child-computer interaction, these findings should be taken into account when designing systems that use pens.

In terms of drawing, children are able to trace simple shapes by 6 years of age, can copy simple shapes using a line grid by age 9, and can copy simple shapes freehand by age 11. Children copy and trace shapes usually starting at the bottom-left and moving up vertically with their first stroke (Birch & Lefford, 1967). Drawing programs should avoid obstacles in this part of the drawing canvas.

Children are capable of writing recognizable characters and numbers by age 4, but these are most often not organized in any particular way. By age 5 or 6, most children are able to print names. Most children master the ability to write uppercase letters by age 7. By age 9, most children gain the ability to space letters correctly (Payne & Isaacs, 2017).

Bimanual coordination involves coordinating the use of both hands in space and time. Common tasks include throwing a ball with two hands, opening small containers, and playing a musical instrument. On computer devices, multi-key strokes on the keyboard, combinations between keyboard and mouse action, and gestures on touchpads or touchscreens make use of bimanual coordination. Basic bimanual coordination is usually achieved by age 2, with the complexity of these types of tasks increasing significantly in the following years (Cech & Martin, 2011).

Hand preference is usually not well established until children reach the ages of 4 to 6. Besides being left- or right-handed, children can also grow up to be ambidextrous (performing at or above their age with both hands) or switched-handers (left-handers who learn to write and draw with the right hand) (Kraus, 2006). In most cases, handedness is not clear until children begin writing at age 6 or 7 (Cech & Martin, 2011). Hand preference is most significant for the skilled use of tools, as well as bimanual actions (Bryden, 2012). One of the most widely used tests for hand preference is the Edinburgh Handedness Inventory, in which people are observed conducting a variety of activities such as writing, using a toothbrush, and throwing a ball (Oldfield & others, 1971). Hand preference is something to take into account when conducting studies using input devices. Hand preference can be a factor in studies that involve children using input devices, but it may be difficult to assess hand preference with very young children.

Reaching movements

Reaching movements use the perceptual motor process. Reaching and pointing movements are usually made up of one initial long movement that gets the hand close to the object, followed by smaller movements to either grasp an object or point at it. Research studies have provided evidence suggesting that visual feedback affects these tasks even while long movements are being conducted. In other words, visual feedback can help adjust movements as they are being made. Proprioception, or the perception of where our body parts are located based on feedback from muscles, joints, and skin, also provides feedback (Rösblad, 2006). Therefore, according to the perceptual-motor process, the feedback must be integrated, processed, and decisions on how to adjust need to be made. The quality and speed of perception, information processing, decision-making, and muscular response will all thus have an impact on children’s performance in these types of tasks. Hence, the importance of motor, perceptual, and cognitive development in children’s performance of simple tasks with input devices on a computer.

The neural pathways used for motor tasks such as repetitive tapping, aiming, and pegboard transportation provide quick increases in speed in early childhood, reaching a plateau with similar speed to that of adults by age 10 (K. Müller & Hömberg, 1992). Reaching trajectories become more direct and less variable, again reaching adult levels by age 10 (Schneiberg et al., 2002). These improvements in performance go together with a reduction in the number of sub-movements required to reach a target and a smooth transition between reaching and grasping movements, once again by age 10 (Kuhtz-Buschbeck et al., 1998). Rösblad found that movements to complete a particular aiming task become more consistent as children get older, with these movements staying almost the same every time by the time children reached the age of 12 (Rösblad, 2006). Lhuisset and Proteau found that while 6-, 8-, and 10-year-old children planned their movements, their plans were still not as consistent as those of adults (Lhuisset & Proteau, 2004). Children also become more proficient with bimanual tasks, especially those involving asymmetric use of the hands (Fagard, 1990). These results are a close match for what has been observed when children conduct operations with input devices (e.g., with the mouse). These studies are reviewed in Appendix B.

Appendix B
Specific Interaction Design Guidelines

Visual design

Visual design is critical to most software and technology development. Below are basic guidelines for common elements used in visual design.

Icons

Visual means of interacting with user interfaces are crucial to the success of software for children who are preliterate or are just beginning to read. Problems with textual interfaces have been noted, for example, by Walter et al. (Walter et al., 1996). Just as in the case of icons for adults, icons for children should be designed so that they represent actions or objects in a recognizable manner, are easily distinguishable from each other, can be recognized as interactive and separate from the background, and have no more visual complexity than what is needed to accomplish the previous three requirements (Hanna et al., 1998; Shneiderman et al., 2016). Icons should also be sized so children can easily click on them. See the Pointing section below for more information on sizing guidelines.

Text

As mentioned earlier, the use of text should be minimized, in particular for children who do not know how to read or are just beginning to read (Druin et al., 2001). Another advantage to having little or no text is that it may make it easier for technologies to be adopted by children who speak different languages. Obvious exceptions to limiting text can be made for software that has reading or writing as a goal.

Visual complexity

High visual complexity can overwhelm any user, let alone children who cannot process visual information as quickly as adults (Kail, 1991). One way of dealing with visual complexity is to use multilayer strategies where children are first presented with few actions and objects and, as they become proficient with these, can move on to add other actions and objects to the user interface (Shneiderman, 2002).

Sound and voice

Very little research has been conducted on the use of sound without considering speech in user interfaces designed for children. Jacko studied children's identification of auditory icons and found that as children get older, they improve their ability to identify icons (Jacko, 1996). There is a growing body of research on voice user interfaces, with many applications discussed in Chapter 8. In terms of specific overarching findings for the design of these systems, recognizing children's speech, in particular at young ages, continues to be problematic (Kennedy et al., 2017; Yarosh et al., 2018).

Interaction styles

Below is a discussion of child-related issues with some common interaction styles: direct manipulation, menus, and text-based interactions.

Direct manipulation

Shneiderman et al. mention three ideas behind the concept of direct manipulation: visibility of objects and actions of interest; rapid, reversible, incremental actions; and a replacement of typed commands by pointing actions on objects of interest (Shneiderman et al., 2016). Most software for children nowadays attempts to follow the ideas behind direct manipulation.

Rapid actions are very important in children's user interfaces because children will often be less patient than adults when using software (Hanna et al., 1998). Children need quick feedback and if they do not get it they are likely to move to another activity. For actions that take too long to complete in time to give quick feedback, children should be given feedback on the status of the action (e.g., through a progress bar) and should still be able to interact with the application and cancel the action if they wish to do so.

Reversibility of actions is also quite important to encourage children's exploration of technologies while keeping them in control. If an action can lead to children losing a drawing they worked on, for example, it will cause a great deal of frustration and will likely lead them to quit using the technology unless they can reverse the action and get their drawing back.

Making actions incremental can also help children by avoiding the need for them to put together complex instructions. When paired with timely and informative feedback, this approach can help children accomplish complex tasks.

Menus

In the broadest sense, children experience menus (i.e., sets of choices) in software all the time. The problems come when these choices are not immediately visible and are arranged in pull-down menus or other types of interactive structures. Indeed, navigation of menu structures has proved problematic for children (Druin et al., 2001; Hutchinson et al., 2006). Even when working with 10- to 13-year-old children using handheld computers, Danesh et al. found that menus that had to be brought up using a soft button were easy to forget (Danesh et al., 2001). The problems, though, are particularly dire with younger children, those in the pre-operational stage, usually aged less than 7 years old, who do not have a good understanding of hierarchies. On the other hand, simple setups, such as those on tablet user interfaces where children can swipe through sets of icons and may remember the location of their favorite choices, appear to work well even for young children.

Text-based interactions

Text can also be problematic if children need to interact with the computer by typing. If children do not know how to type, this approach can significantly slow down interactions and lead to frustrating experiences. Spelling can also cause problems if entering commands or search terms (Hourcade & Perry, 2009; Walter et al., 1996). For this reason, programming languages for children have moved from being text-based to have a more visual approach, as discussed in Chapter 7.

Pointing

Pointing is still the most common method for children to interact with technology. The ways in which it is accomplished have become quite varied over the years. Interactions with a mouse, touchpad, or other indirect pointing devices are still quite common, especially for older children. With smartphones and tablets there has been a dramatic increase in the use of direct touch. In addition, motion-based sensor technologies also involve pointing actions.

The following is information on what types of devices are most appropriate for children, how children perform in pointing and dragging tasks, and how they use mouse buttons.

Age-appropriate devices

Much of the early research with children and input devices focused on identifying the most appropriate pointing input device for children. The mouse came out the winner in most studies when compared to a variety of devices such as trackballs, joysticks, and keyboards (T. Jones, 1991; King & Alloway, 1992, 1993; G. L. Revelle & Strommen, 1990). Particularly interesting was the study conducted by Revelle and Strommen, who found that the mouse provided advantages to preschool children but only after practicing with it for some time (G. L. Revelle & Strommen, 1990). These longitudinal effects are something to take into account when evaluating input devices. The only exception to the mouse coming out on top was a study by Strommen et al. with 3-year-old children, where the trackball was favored (E. F. Strommen et al., 1996).

The need to use the mouse became prevalent in school use of computers during the 1990s, to the point where some considered the use of pointing devices an important skill for children. For example, Lane and Ziviani, who are occupational therapists, developed the *Test of Mouse Proficiency* with the aim of identifying children who have difficulty using a mouse in order to offer them appropriate interventions. The test assesses children's proficiency through four games, each requiring the use of a different mouse skill: pointing and clicking on stationary targets, pointing and clicking on moving targets, drawing, and dragging and dropping items (Lane & Ziviani, 2002, 2003).

Little attention has been paid to issues of input device size. Hourcade et al. visited this issue in a study comparing 4- and 5-year-old children's performances with small and regular sized mice. The results suggest that mouse size does not affect performance. One limitation of this study is that all participants had experience using a regular-sized mouse (Hourcade et al., 2007). The results, though, are in line with previous observations by researchers, which point at mouse size not making a difference (Crook, 1992).

Surprisingly, until smartphones and tablets became popular, little work had been conducted on evaluating the merits of direct pointing technologies, such as styluses and touchscreens. However, the past 10 years have included a new wave of research on the use of direct input. Another challenge with smaller devices is their small screen size, which makes it impossible to present or manipulate the same amount of content as on a desktop display. Not surprisingly, there are cases with these devices where challenges with screen size have been documented for tasks that are difficult to complete without sufficient screen space (Luchini et al., 2003). More on the topic of mobile devices can be found below under the Touch and Gestures section.

Development of pointing abilities

A well-established finding with respect to children and pointing is that pointing skills, just like other motor skills, develop with age. This means that younger children will not be as accurate as older children when pointing, regardless of the pointing method they use. For this reason, younger children require larger target sizes than older children in order to reach the same level of accuracy. Targets that are too small can often lead to frustration and bring difficulty to the use of technology in an area where it is not needed,unless the goal was to help children improve their motor skills. Frustration with small targets can also result in behaviors such as quickly and repeatedly clicking the mouse (Hourcade, Perry, et al., 2008) or tapping a screen until something happens (Anthony et al., 2012), which brings additional issues when writing software to handle all those click or touch events.

More specifically, a look at the literature on children and pointing tasks reveals a long record of studies dating to the 1970s showing that young children's pointing performance is below that of older children and adults (Kerr, 1975; Salmoni & McIlwain, 1979; Sugden, 1980; Wallace et al., 1978). Several studies have shown that these differences persist when children use computer pointing devices (Crook, 1992; Hourcade, Bederson, Druin, et al., 2004; R. Joiner et al., 1998; T. Jones, 1991; King & Alloway, 1993). A study by Hourcade et al. conducted with 4- and 5-year-old children showcased the differences between the preschool children and young adults also participating in the study when conducting point-and-click tasks. There were clear differences in terms of accuracy, with 4-year-old children needing targets four times larger in diameter than young adults to achieve an accuracy level of 90 percent (Hourcade, Bederson, Druin, et al., 2004).

A follow up analysis of the same study's data looking at sub-movements in pointing tasks suggested that the differences in performance between adults and children were largely due to the inaccuracy of children's sub-movements near the target both in terms of direction and length (Hourcade, 2006). There was a balance between undershoots and overshoots of the target and with larger targets, both children and adults tended to point at an area of the target closest to the location of the mouse cursor.

The easiest way to help young children with pointing is to make targets large enough. One challenge is that programmers can only control the number of pixels assigned to a target and cannot control the actual motor space that the targets occupy (i.e., how much one would have to physically move the mouse from one end of a target to the other). Furthermore, displays with higher resolutions can also lead sizes in pixels to lose importance. That said, in Hourcade et al.'s first study (Hourcade, Bederson, Druin, et al., 2004), 4-year-old children achieved a level of accuracy of 90 percent with targets that had a diameter of 64 pixels, 3.6mm in motor space, and 23.7mm on the screen. 5-year-old children achieved the same level of accuracy with targets half the diameter (i.e., 32 pixels). Young adults reached 90 percent accuracy with targets 16 pixels in diameter.

When using indirect pointing devices (including motion tracking devices), the other way to help children is to slow down the speed of the cursor. Slowing the speed of the cursor can provide for more precision when pointing at targets, but can also cause frustration in getting to targets, especially given increasingly larger monitors and screen resolutions. Changing these settings is something that can be done by parents or teachers if they notice children having difficulty. An alternative is to slow down the cursor only when the pointing device is moved at slow speeds. More research needs to be conducted on whether this is a good option for children. One problem with the above-mentioned solutions (including larger targets) is that they do not necessarily prepare children for more difficult pointing tasks.

Other solutions that have been suggested for adults also have limitations. Bubble or area cursors, which make the active area of the cursor larger than a point, do not help in cases where targets are clustered (Grossman & Balakrishnan, 2005; Worden et al., 1997). The same problem happens with semantic pointing, where targets look smaller than their active area (Blanch et al., 2004). Expanding targets are unlikely to work because they attempt to predict the target the user intends to point at partly based on the direction of movements, and young children's movements tend to lack directional precision (Hourcade, 2006; McGuffin & Balakrishnan, 2002; Zhai et al., 2003). All of the above solutions require knowledge of the location of the targets and thus would have to be implemented in each software title that wanted to use them, which would make them less likely to be adopted.

Hourcade proposed an alternative approach designed for children that detects when they are having difficulty pointing at a target based on the characteristics of their sub-movements. It is based on the observation that sub-movements near a target tend to be slower and shorter than other sub-movements. This information could be used to trigger a precision pointing mechanism (e.g., slowing down the speed of the cursor) (Hourcade, 2006). Hourcade et al. used this approach to develop *PointAssist*, which enabled 4-year-old children in a study to achieve accuracy rates close to those of 18- to 22-year-old adults in previous studies that used very similar testing conditions (Hourcade, Perry, et al., 2008).

The main advantages of *PointAssist* are that it does not need to know about the location of targets and thus can be implemented with software that runs in the background and affects all applications. Another advantage is that it works as a scaffold. When children cease to have difficulty in pointing tasks, the precision mode does not get triggered (Hourcade, Perry, et al., 2008).

Dragging

Drag-and-drop interactions have been challenged in children's software by click-move-click interactions where users click on an object to move it, move the mouse to a destination, and click again to drop the object. One could think of the same issue with touchscreens, where the options would be drag-and-drop versus touch-move-touch. Click-move-click interactions assume that the objects are there to be moved only and not to invoke an action. Even in this case, there is controversy as to which type of interaction serves children best.

Joiner et al. conducted two studies comparing drag-and-drop to click-move-click. They found that 5- to 6-year-old children took less time on average to complete tasks using the click-move-click technique and committed less errors. The problems were magnified for long-distance drag-and-drop tasks and did not seem to be present in short distance drag-and-drop tasks. There were no differences between click-move-click and drag-and-drop for older children (R. Joiner et al., 1998).

Inkpen recommended the use of click-move-click interactions over drag-and-drop interactions (K. M. Inkpen, 2001). In two experiments, 9- to 13-year-old children were quicker and committed less errors when using click-move-click interactions. There were some peculiarities to the way the click-move-click interactions were implemented that may partly explain differences in the results of other studies. The click-move-click interactions, as described in detail for the second experiment, could be more precisely described as press-move-press interactions, as the release of the mouse button was not taken into account. This method contrasts with the standard way that clicks work in Microsoft Windows, for example, where clicks require that the mouse cursor be on a target as the mouse button is pressed and released. In other words, pressing the mouse button inside a target and releasing it outside does not generate a click event on a target in Windows. The other design decision that favored click-move-click interactions in these studies is that a drop error in the click-move-click condition kept the target “picked-up.” In other words, if children missed the target receptor when clicking, they could try again and again with no penalty. Under the drag-and-drop condition, however, if children released the mouse button somewhere outside the target receptor, the target would go back to its original location and would have to be picked up again.

Conducting a study almost a decade after Inkpen and Joiner, Donker and Reitsma found the opposite result, with 5- to 7-year-old children conducting drag-and-drop tasks faster and with less errors than when following a click-move-click approach (Donker & Reitsma, 2007b). This study used letters as items to move, which had different sizes and aspect ratios, making it difficult to compare results with other studies. An additional experiment found that 5- to 7-year-old children's and adults' drag-and-drop errors are not related to difficulty in keeping the mouse button down, but to errors at the beginning and end of a drag-and-drop operation (Donker & Reitsma, 2007a). One of the most interesting findings was that movement distance did not affect the successful completion of a task. This is the opposite of what Joiner et al. observed (R. Joiner et al., 1998). Donker and Reitsma recommend that feedback be provided to children when a target can be picked up and when it can be dropped off on a receptor by, for example, changing the appearance of the mouse cursor (Donker & Reitsma, 2007a).

Barendregt and Bekker revisited the question and found that the children with whom they worked expected interactions, such as drawing a line, to be accomplished through dragging and continued to use dragging even if it was possible to accomplish the same tasks through click-move-click (Barendregt & Bekker, 2011).

The conflicting results are somewhat puzzling.These inconsistencies may be due to young children, especially 5- to 6-year-old children, having more experience in the 2000s than they did in earlier studies in the 1990s and therefore having fewer problems with drag-and-drop tasks. Barendregt and Bekker's study seems to point in this direction (Barendregt & Bekker, 2011). Another explanation could also be that the mice used in the 2000s made it easier for children to complete the tasks when compared with older mice that may have had buttons that were not as well designed, as well as mechanical methods for tracking position (through a ball) that were not as accurate or smooth as those used in optical mice.

While there is no clear answer as to what the optimal choice is, the history of results suggests that drag-and-drop may be the better choice currently, most likely due to children's greater experience with computers and the use of higher quality input devices.

Another frequent use of dragging is for selecting a number of objects. For these situations, Berkovitz recommends that marquee selection of objects be implemented by having children draw a circle instead of a box around items to select them. He found this advantageous in work with 6- and 7-year-old children (Berkovitz, 1994).

Use of mouse buttons

Hourcade et al. studied the use of mouse buttons by 4-and 5-year-old children as well as young adults who were not told which button to use. The software the children used during the study responded to clicks from both the left and right mouse buttons. While all adults used the left mouse button in every task, and most of the 5 year olds (10 out of 13) also used the left mouse button exclusively, most 4 year olds used a combination of left and right button clicks. A more recent study with 4- and 5-year-old children who had greater experience using a mouse found that a majority of the children used the left mouse button exclusively. Still, 10 percent of the children used the left mouse button less than 90 percent of the time (Hourcade, Bederson, & Druin, 2004a).

Three strategies can be used to prevent frustration in young children who do not get what they expect when they click. One is to provide the same functionality through all mouse buttons. This approach, for example, was used successfully in *KidPad*

(Hourcade, Bederson, & Druin, 2004b). The other approach is to provide functionality only through the left mouse button, with other buttons not providing any functionality and/or providing feedback on button pressing. The advantage of this approach is that it could prepare children better for applications where different buttons provide different functionality. On the other hand, such an approach could lead to frustration if children click on the right button, and nothing happens. The third option is for children to use platforms where mice have only one button (e.g., Macintosh), which avoid these problems altogether.

Touch and gestures

Studies on children's touch interactions have slowly emerged over the years. A key feature of touch interactions is that they have significantly lowered barriers for children to use computers, which previously were difficult to use for children younger than 4 years of age due to the necessity of using a mouse and keyboard as input devices. Through a study of YouTube videos, Hourcade et al. learned that a majority of children aged 12 to 17 months showed at least moderate ability to use touchscreen-based tablets, coinciding with children's ability to make a pointing motion with their index finger (Hourcade et al., 2015). At the same time, as with indirect device input, there are clear differences between young child and adult abilities that manifest themselves in different patterns of interaction (Vatavu, Anthony, et al., 2015). Below is an overview of relevant studies on this topic, but for current guidelines the best resource is Soni et al.'s framework for touchscreen interaction design recommendations for children, which include cognitive (e.g., visual design), physical (e.g., appropriate target sizes and gestures), and socioemotional factors (customization, activity structure) (Soni et al., 2019).

Lisa Anthony and her colleagues have conducted a series of studies to develop guidelines for children's touch interactions. In a study comparing the touch and gesture performance of children aged 7 to 16 years old and adults, children were able to achieve reasonable tap accuracy (about 90 percent on average) with

9.5mm targets, and even better accuracy (above 95 percent) with 12.7mm targets. In terms of gestures, children had over 90 percent accuracy when drawing gestures in the shape of a triangle, an X, and a K (Anthony et al., 2012).

Anthony et al. also studied gestures through a study with children, teenagers, and adults. In particular, the researchers studied the impact of providing visual feedback on the gestures by showing a visual trace as the input is made by the user. The gestures in the study included letters, numbers, basic symbols, and shapes. While having visual feedback changed the gestures, it did not affect the ability of a gesture recognizer to correctly classify them. At the same time, most users preferred having the visual feedback. Based on the findings, the researchers recommend providing visual feedback for gestures on mobile devices, including only gestures that are familiar to users, and testing gesture sets with recognizers in advance. As expected, accuracy in completing gestures went up with age, from an average nearing 77 percent for 10-year-old children to about 91 percent for adults (Anthony et al., 2013).

Nacher et al. conducted a similar study, but with children aged 24 to 38 months. They found all children had high rates of success with tap, drag, scale, and one-finger rotation tasks, while they had greater difficulty with double-tap, long-press, and two-finger rotation tasks. However, children conducted all tasks with very large targets (Nacher et al., 2015).

In a study with 89 children aged 3 to 6, Vatavu et al. studied tap, double-tap, dragging one target, and simultaneous dragging of two targets on a tablet and a smartphone. Targets were 8mm and 20mm in diameter for the smartphone and tablet respectively, but in both cases had an active area of 23mm centered around the target. Children had very high tap completion rates (98.7%), reasonable double-tap rates (82.8%), good single-item drag rates (92.0%), and low simultaneous multiple-item drag rates (53.7%). Children had higher completion rates with smartphones than tablets and older children had higher completion rates than younger children (Vatavu, Cramariuc, et al., 2015). Note that differences between these results and those of Nacher et al. above (Nacher et al., 2015) could be due to a combination of different instructions and different implementations of event recognition, among other factors.

Hiniker et al. conducted a study with 2- to 5-year-old children to better understand the effectiveness of in-app instructions to perform gestures. They found that children younger than age 3 needed an adult to model the gestures, while older children did best with audio instructions (Hiniker, Sobel, Hong, et al., 2015).

Most smartphones and tablets now support multitouch capabilities. Looking at larger tabletops, Rick et al. (2009) studied 15 groups of children aged 7 to 9 years old. The researchers asked the children to complete a task that involved setting up a classroom, including manipulating tables and assigning seating positions to children in the class. They compared single-touch to multi-touch modes of interaction. They found that multi-touch led to more equitable participation and that children tended to interact all over the table, with more attention paid to areas closer to where they were located (Rick et al., 2009).

Also working with large displays, Anthony et al. studied the impact of orientation (i.e., table vs. wall) on visitors to a science museum, including children and their parents. They found that visitors performed standard touchscreen gestures with both setups, that children were more likely than their parents to try new gestures, and that visitors were more likely to perform two-handed gestures on the wall setup (Anthony et al., 2016).

Smartphones and tablets also have gyroscopes, accelerometers, and cameras that can help with tracking the position and orientation of the device, enabling gestures by moving the device. McNally et al. (2014), for example, compared the use of such gestures to a touch-based user interface to interact with a second-language learning application. While they found that most children preferred touch-based interactions, some specific interactions appeared to be easier when using mid-air gestures (McNally et al., 2014).

Tangibles

Many researchers have explored the use of tangible user interfaces in their technology. These are physical items that are either augmented with sensors and actuators (e.g., buttons and screens) or have unique identifiers in them that can be identified through computer vision. Tangible setups enable users to interact with technology by manipulating these physical items, instead of manipulating items on a screen. There is evidence that tangible approaches may increase motivation, facilitate social engagement, and even make some tasks, such as solving puzzles, more manageable (A. N. Antle et al., 2009).

One area where tangibles have been used is in museum exhibits. Horn et al. discussed the lessons learned during a deployment at the Boston Museum of Science. Their system followed five design considerations to make it work best in a museum setting by making it: inviting, easy to learn, engaging, supportive of group interaction, and inexpensive and reliable (Horn et al., 2008).

Metatla et al. presented an exploration of tangibles and scents to understand the emotions they may elicit. In a study with 10- to 17-year-old children, they found that children tended to associate a round shaped item combined with vanilla scent with a calming emotion. They also associated an object with angular shapes combined with lemon scent with an arousing emotion (Metatla et al., 2019).

Full-body interactions

Full-body interactions are enabled by a variety of systems using cameras that can track children’s bodies, enabling them to interact with computer systems by moving limbs, and sometimes even by walking, running, or jumping. One benefit of full-body interactions is that for group activities, it can result in children perceiving greater levels of collaboration when compared to collaborating on desktop environments (Malinverni & Burguès, 2015). Most of these interactions have been used in relation to computer-supported physical activity and also with neurodiverse children, as discussed in Chapter 11.

Augmented reality

The availability of high-performance image and graphics processing has enabled the development of augmented reality technologies in which users can experience the world with added virtual items. Systems such as Microsoft's *HoloLens* smart glasses enable these experiences, although smartphones are also capable of the same. As these technologies have become available, researchers in child-computer interaction have begun to explore them, mostly for learning applications, with some researchers working on general-purpose systems (Cheung et al., 2020).

Some augmented reality applications require users to select items. Radu et al. explored two selection techniques with 5- to 10-year-old children: crosshair selection and finger selection. Their main finding, consistent with other research on input methods, was that younger children were slower and less accurate than older children. They also found that finger selection was quicker than crosshair selection (Radu et al., 2016).

Malinverni et al. studied two different augmented reality paradigms in the context of groups of elementary school children playing a mystery solving game with mobile devices. One of the paradigms is referred to as Window-on-the-World and consists of merging computer-generated images with images captured by the device's camera. The other paradigm is called World-as-Support. It enables users to project items on their surroundings and use the physical world to interact with them. Through their study the authors found that children collaborated in different ways, with role divisions and parallel work more likely to take place under the

Window-on-the-World condition, while children in the World-as-Support paradigm tended to go through the experience together without taking on specialized roles (Malinverni et al., 2018).

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