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TOY USER INTERFACES: Design tools for Child-Computer Interaction

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Tese apresentada ao Programa de Pós-Graduação em Ciência da Computação da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de doutor em Ciência da Computação. Área de concentração: Mídia e Interação.

Orientadora: Judith Kelner

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Anna Priscilla de Albuquerque

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I dedicate this thesis to my daughter Serena Thérèse de Albuquerque Wheler, my husband Michael Wheler, and our family. You make my future brighter, my life lighter, and my heart warmer.

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ABSTRACT

A Toy User Interface (ToyUI) is a setup combination of one or more toy components with other hardware or software components. As part of emerging technologies that permeate the Child-Computer Interaction (CCI) domain, a ToyUI setup can combine toy components with social robots, smartphones, tablets, game consoles, and other gadgets. This thesis presents and compiles a collection of design tools to support interdisciplinary stakeholders in prototyping innovative ToyUI setups. The design tools aim to assist the CCI research community and industries seeking more design opportunities while being aware of the potential ethical and privacy-related issues for designing integrated artifacts for CCI. The research methods apply the Design Science Methodology framework to assess the problem context and propose a treatment design to improve this context. The design tools follow a Human-Centered Design (HCD) perspective covering the steps from inspiration to ideation and implementation, comprising user research, brainstorming, data collection planning, and low to high-fidelity prototyping tools. This thesis also discusses digital versions of the tools to support remote teamwork and education in the context of the COVID-19 global pandemic. Qualitative evaluation in a project-based learning setting covers a series of case studies in seven institutions from Brazil, Canada, and Germany. In total, 255 stakeholders experienced different versions of the design tools, implementing 67 ideas among low and high-fidelity prototypes and digital prototypes. The results highlight lessons learned from the evaluation and how the case studies supported improving the design tools. It also compares the challenges of face-to-face training and remote training challenges during the social distancing context. The proposed tools can become a suitable approach to support training relevant Information Technology and User Experience design skills in interdisciplinary stakeholders. The design tools can improve accessibility in future works, such as offering tangible and block coding to support children, youth, and people with visual impairments, including supporting educators and non-experts to develop ToyUI solutions for Science, Technology, Engineering, and Mathematics (STEM) education.

Keywords: Child-Computer Interaction. Smart Toys. Social Robots. Design Tools. Rapid Prototyping.

RESUMO

Interfaces de Usuário para Brinquedo - do Inglês, Toy User Interfaces (ToyUI) é uma integração de um ou mais brinquedos com outros componentes de hardware ou software. ToyUI faz parte das novas tecnologias que permeiam o domínio da Interação Criança-Computador (ICC), uma ToyUI pode integrar brinquedos e robôs sociais, smartphones, tablets, consoles de jogos e outros dispositivos. Esta tese propõe e compila uma coleção de ferramentas de design para dar suporte a equipes interdisciplinares no desenvolvimento de ToyUI. As ferramentas de design visam auxiliar a comunidade de ICC no desenvolvimento de novas ToyUI, cientes das questões éticas envolvidas ao projetar artefatos integrados para crianças. O método de pesquisa aplicado é a Ciência do Design, visando avaliar o contexto do problema e propor uma intervenção que melhore este contexto. As ferramentas de design seguem uma perspectiva de design centrado no usuário englobando as etapas da inspiração, ideação e implementação, compreendendo pesquisa de usuário, geração de ideias, planejamento de coleta de dados e ferramentas de prototipagem de baixa e alta fidelidade. Esta tese também propõe versões digitais das ferramentas para apoiar o trabalho remoto em equipe como no contexto da pandemia global do COVID-19. A avaliação qualitativa em um ambiente de aprendizagem baseado em projetos ocorreu em uma série de estudos de casos, sendo sete instituições distribuídas no Brasil, Canadá e Alemanha. No total, 255 indivíduos experimentaram diferentes versões das ferramentas, implementando 67 ideias entre protótipos de baixa e alta fidelidade e protótipos digitais. Os resultados destacam as lições aprendidas com a avaliação e como estudos de casos promoveram melhorias nas ferramentas propostas. Também foram comparados os desafios do treinamento presencial com os desafios do treinamento remoto durante o contexto do distanciamento social. As ferramentas propostas demonstram ser uma abordagem adequada para o treinamento de habilidades de Design de Experiência do Usuário e Tecnologia da Informação em equipes interdisciplinares. Como trabalhos futuros, as ferramentas podem incorporar acessibilidade, oferecendo codificação tangível ou em blocos permitindo o uso por crianças, adolescentes e pessoas com deficiência visual, bem como facilitar o uso por educadores e não especialistas no desenvolvimento de soluções ToyUI para Ciência, Tecnologia, Engenharia e Matemática.

Palavras-chaves: Interação Criança-Computador. Brinquedos Inteligentes. Robôs Sociais. Ferramentas de Design. Prototipação Rápida.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

AI	Artificial Intelligence
AR	Augmented Reality
AUAS	Augsburg University of Applied Sciences
BLE	Bluetooth Low Energy
CCI	Child-Computer Interaction
cHRI	Child-Robot Interaction
CNC	Computer Numerical Control
CPG	Children's Play & Games
CU	Central Unit
DC	Direct Current
DIY	Do-It-Yourself
DoF	Degrees of Freedom
DSM	Design Science Methodology
FSR	Force Sensing Resistors
GAF	Games & Applications for Fun
GDD	Game Design Document
GDPR	General Data Protection Regulation
GPS	Global Positioning System
GRVM	Virtual Reality and Multimedia Research Group
GUI	Graphical User Interfaces
HCD	Human-Centered Design
HCI	Human-Computer Interaction
HMD	Head-Mounted Displays
HRI	Human-Robot Interaction
IC	Integrated Circuit
IDE	Integrated Development Environment
IFPE	Instituto Federal de Educação, Ciência, e Tecnologia de Pernambuco
IMU	Inertial Measurement Unit
IoT	Internet of Things
IPS	Indoor Positioning System

IR	Infrared
IST	Interactive Social Toys
IT	Information Technology
LED	Light-Emitting Diode
LGPD	General Personal Data Protection Law
LPS	Local Positioning System
MAC	Media Access Control
MR	Mixed-Reality
NFC	Near-Field Communication
NGO	Non-Governmental Organization
NPID	Non-Personal Identification
PCB	Printed Circuit Board
PD	Personal Data
PUI	Playful User Interfaces
QR	Quick Response
RCT	Rapid Coding Tool
RF	Radio Frequency
RFID	Radio Frequency Identification
ROS	Robot Operating System
SDK	Software Development Kit
SENAC-GO	Serviço Nacional de Aprendizagem Comercial de Góias
SGA	Serious Games & Applications
SMD	Surface Mounted Device
STEM	Science, Technology, Engineering, and Mathematics
SUS	System Usability Scale
ToyUI	Toy User Interface
TUI	Tangible User Interfaces
UFPE	Universidade Federal de Pernambuco
UML	Unified Modeling Language
UOIT	Ontario Tech University
UPS	Unidentifiable Positioning System
UX	User Experience
WoZ	Wizard of Oz

CONTENTS

1 INTRODUCTION

The present chapter starts introducing novel technologies in the Child-Computer Interaction (CCI) domain. The second section introduces the research problem addressed in this thesis, including research motivation, methods, and goals. The third section details the thesis presentation.

1.1 CHILD-COMPUTER INTERACTION

CCI is a domain from Human-Computer Interaction (HCI) that refers to the design, evaluation, and implementation of interactive computer systems for children, considering the general impact of technology on children and society (HOURCADE, 2015). In recent years, the extent of computing artifacts that permeates the CCI domain has increased dramatically. Many CCI artifacts are personal computers, smartphones, tablets, game consoles, voice assistant devices, smart toys, smartwatches, and household robots. These artifacts blend into a child's life, while several unexpected and sometimes humorous CCI emerge. For instance, unexpected and humorous CCI may emerge when a child interacts with voice assistant devices like *Amazon Echo* (Amazon, 2021) and *Google Home* (Google, 2021). In a study on how children (6–10 years old) interact and perceive voice assistant devices, researchers noticed children of all ages seeking to engage in humorous dialogues rather than operative tasks, such as requesting the device to reproduce farting or burping noises (FESTERLING; SIRAJ, 2020).

Children's expectations towards computing technologies significantly differ from adult users, influencing CCI motivations and outcomes (RICHARDS, 2019). Voice assistant devices aim to support various operative tasks, such as accessing the Internet to provide contextual information (e.g., weather, time, locations, etc.) or seeking keywords or topics online (e.g., cooking recipes and learning issues) (HOY, 2018). They can also improve accessibility features and facilitate interaction with other connected devices in the house (e.g., television, media players, etc.). In this scenario, some unexpected and more concerning CCI can include a child accessing age-inappropriate content online or accidentally purchasing items using the parent's stored billing information. Thus, it is essential to consider specific user and security requirements when developing voice-based technology supporting CCI (MCREYNOLDS et al., 2017).

CCI can be introduced in the first stages of child development, opening opportunities to engage a child in CCI activities while facilitating parental monitoring tasks (PATIL et al., 2018). For example, parents can introduce monitoring technologies to a newborn child using a smart monitoring system, like the smart camera *Cubo AI Plus* (Cubo AI, 2021) or the smart sock *Owlet* (Owlet Baby Care, 2021). Smart monitoring systems permit monitoring a child's physical and physiological status using various technologies, such as sensory technology, machine learning, and computer vision (JABBAR et al., 2019). Smart features can include categorizing sleeping patterns, detecting risky situations, and monitoring the room or body's temperature, breathing, and heart rate. *Chirpy* is a smart owl toy that can detect and soothe a crying baby by flapping its wings and singing a song while emitting crying alerts to parents by sending notifications (DESAI; MCCANN; COROS, 2018). Similarly, the *Cubo AI Plus* offers CCI features, such as playing lullaby songs to the child in the crib and detecting body motion to take automated pictures.

In addition to parental monitoring features, CCI can also support training a series of physical and social abilities in different child development stages (KEWALRAMANI et al., 2020). Physical abilities can range from training a child's fine motor skills (pick and place) to gross motor skills (standing and walking) (VANDERMAESEN et al., 2014; TAM; GELSOMINI; GARZOTTO, 2017; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018; BORGHESE et al., 2019; YAMAMOTO et al., 2020). Social and cognitive abilities may include developing a child's eye gaze and joint attention skills and overcoming speech impairments (HENGEVELD et al., 2009; BROK; BARAKOVA, 2010; FIKAR; GÜLDENPFENNIG; GANHÖR, 2018; CROVARI et al., 2019; CAÑETE; LÓPEZ; PERALTA, 2021). CCI artifacts to support different child development stages include computer games, voice assistant devices, smart toys, and companion robots (BELPAEME et al., 2018; NEUMANN, 2020). For example, *NogginStick* (SmartNoggin, 2021) is a smart baby rattle that uses an RGB Light-Emitting Diode (LED), motion, and capacitive touch sensors to support CCI in the early stages of baby development as training gaze coordination and a range of motor skills. Many CCI studies present promising benefits of using robot technology to support neurodivergent children on training social skills, which can become valuable tools for educators, child therapists, and parents (COSTA et al., 2017; GARZOTTO; GELSOMINI; KINOE, 2017; ALHADDAD et al., 2018; DICKSTEIN-FISCHER et al., 2018; FISICARO et al., 2019).

Nonetheless, the complexity and number of CCI artifacts grow more attractive over the years while raising concerns for the parents regarding screen-time consumption and online privacy risks (EISEN; MATTHEWS; JIROUT, 2021; PRASAD; RUIZ; STABLEIN, 2019). In a study, authors investigated factors that can influence children's (0—8 years old) screen-time consumption in four types of media devices: television, computers, smartphones, and tablets (LAURICELLA; WARTELLA; RIDEOUT, 2015). Results indicate that parents' screen-time can strongly influence their child's screen-time in all types of media devices, and the family environment must be fully considered when developing policies to influence children's screen media usage. In a privacy workshop with 25 children (10—11 years old), the authors found out that privacy issues mainly concerned strangers finding their addresses for most children, and they experience the concept of privacy with many different meanings and relations (BROOKS; MOELLER, 2019). In another study, researchers surveyed parents and adolescents (12—18 years old) about behaviors and awareness towards online privacy risks (SHIN; KANG, 2016). Results show evidence that privacy awareness does not determine adopting privacy protection behaviors. Instead, adolescents are likely to disclose personal information online due to various social factors, such as communicating online with friends and peers or participating in online gaming sessions. This study also reveals that instructive parental mediation based on parent-adolescent communication can be more effective than restrictive parental mediation based on rule-making and controlling information disclosure (FORTES et al., 2020).

In summary, CCI artifacts can bring a series of benefits to support child development milestones. However, at the same time, they can raise risks and concerns to both parents and children (e.g., online privacy risks and excessive screen-time). Adequate methods and tools to design, implement, and evaluate CCI artifacts play a significant role in ensuring those benefits while mitigating potential risks during system development (SHASHA et al., 2018). This thesis implements a collection of tools supporting the design, implementation, and evaluation of CCI artifacts (i.e., interactive computing systems that target children as their primary users). More specifically, this research supports the design of novel technologies that integrate software and hardware computing components. This CCI cohort's importance and urgency come from the increasing popularity of the Internet of Things (IoT) and related technologies in the household and educational and healthcare institutions (MANCHES et al., 2015; MASCHERONI; HOLLOWAY, 2019). IoT refers to the networked interconnection of everyday objects, often equipped with ubiquitous intelligence, which leads to a highly distributed network of devices communicating with humans and other devices (XIA et al., 2012). IoT explores various technologies and research topics such as sensory technology, connectivity protocols, distributed and cloud processing models, and cybersecurity and privacy-related issues (ALSHOHOUMI et al., 2019).

1.2 RESEARCH PROBLEM

The consumer industries are continuously introducing novel technology targeted at children, reflecting on the increasing number of smart toys and other CCI artifacts available in the market (MASCHERONI; HOLLOWAY, 2017). Hardware–software integration in CCI industries combines mobile computing industries and traditional toy and entertainment industries (DHAR; WU, 2015). Examples of integrated CCI artifacts include *LEGO Mindstorms EV3* robot kits (The LEGO Group, 2021), Augmented Reality (AR) educational toys for tablets *Osmo* (Tangible Play, 2021), and smart dolls like the former *Hello Barbie* (Mattel, 2015—2019). In most cases, the classic setup of these CCI artifacts integrates at least one physical toy component (a smart toy) and a companion software component (RAFFERTY et al., 2017). However, this integration does not always come as fluid as desired since bridging the physical and virtual play gap remains challenging. Challenges are mostly related to delivering integrated CCI experiences to the users and ensuring children's privacy rights. This thesis aims to overcome these two main challenges by supporting the training of problem-solving skills and decision-making skills, proposing a collection of design tools to intervene in system development stages.

Hardware–software integration challenges can start in the early stages of system development. For instance, challenges can start from inspiration to propose innovative ideas supporting physical and social play activities while minimizing screen-time interaction. Other challenges are designing systems targeting a specific audience (e.g., autistic individuals or individuals with physical disabilities or reduced mobility) or mixing different audiences promoting social inclusion. Challenges related to integrated implementation include supporting distributed interaction and interoperability of connected devices (e.g., systems collecting data from multiple sensors or using different communication protocols). Another significant challenge is how systems designed to collect contextual information can prevent potential ethical issues related to children's privacy rights to Personal Data (PD) protection (ALBUQUERQUE et al., 2020). According to European General Data Protection Regulation (GDPR), PD consists of anything containing directly or indirectly compromising information that can expose user privacy and allow the singling out of individual behavior (EU, 2016). PD includes the individual's name, his/her identification number, geolocation data, and an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural, or social identity of that individual. The Brazilian General Personal Data Protection Law (LGPD) also refers to the PD definition since LGPD is based on GDPR (PINHEIRO, 2020).

Integrated CCI artifacts collect, manage, and store user data, including PD, to support essential system' functionalities. The goals behind a system using PD are varied. For example, location-based applications track Global Positioning System (GPS) data in real-time to determine a child's location and to trigger specific play content (POURCHON et al., 2017). Educational toys may store a child's PD so that teachers, parents, or occupational therapists can further analyze their performance (BONILLO et al., 2019; HO et al., 2019; RIHAR et al., 2019; BORGHESE et al., 2019). Artifacts supporting CCI through social play intend to promote communication among the users or between the user and the toy component. Collecting PD, including voice, image, and video, is often standard in these scenarios (MCREYNOLDS et al., 2017). Artifacts may collect children's PD to design improvements in future versions, such as adding new contents and valuable features, after providing complete transparency, and obtaining parental consent (MILKAITE; LIEVENS, 2019). A significant research problem is providing the CCI community with adequate tools to support problem-solving and decision-making in different system development stages (e.g., inspiration, idea generation, data collection planning, and prototyping). For example, an adequate tool supporting data collection planning in problem-solving can help define how user data can allow essential system' functionalities. A tool can also support determining what types of data are necessary to supply the system's needs, including selecting strategies for data collection and implementation in a decision-making process.

Data management aspects are also affected by other system development decisions. A common practice in the toy Industry is implementing software functionalities using Information Technology (IT) outsourcing companies. Once creators may be part of different interdisciplinary teams (and companies), they can perform parallel tasks during system development. For instance, the *Hello Barbie* doll offered Artificial Intelligence (AI) features by recording and processing a child's voice to establish a reasoning-based dialogue with the child (MCREYNOLDS et al., 2017). The doll offered a set of preexisting dialogue models. It used an embedded microphone to listen and record the child speaking and voice processing services in the cloud, using a connected mobile application via a local Wi-Fi network. The *Hello Barbie* trajectory associates with numerous privacy concerns (e.g., data security vulnerabilities, unclear privacy policies, etc.) (MANTA; OLSON, 2015; JONES; MEURER, 2016a; MOINI, 2016; TAYLOR; MICHAEL, 2016; MERTALA, 2020; HABER, 2020). Privacy issues can potentially impact parents' perception and purchase intent (FANTINATO et al., 2018). In 2019, *PullString*, the IT outsourcing company responsible for providing voice processing services to the *Hello Barbie* companion app, finalized their services with *Mattel*. However, their services' termination was motivated by economic interests from the parties involved. Hiring the IT outsourcing company to develop essential product functionalities (e.g., voice processing services) led to this toy line' discontinuity. Other toy lines that faced similar privacy and IT outsourcing issues are *Dino* (Cognitoys, 2015—2019), *CloudPets* (Spiral Toys, 2015—2018), *I-Que Intelligent Robot* and *My Friend Cayla* (Genesis Toys, 2014—2017), *Toy-fi Teddy* (Dragon-i Toys, 2014—2017), and *Furby Connect* (Hasbro, 2016—2019). Providing interdisciplinary teams with the same structured and integrated design tools can facilitate communication between creators and IT outsourcing teams and perform iterative system development tasks.

1.2.1 Research Motivation

Different authors have suggested training a set of essential skills to support the CCI community to overcome challenges related to hardware–software integration and cybersecurity (DHAR; WU, 2015; TYNI; KULTIMA, 2016; SHASHA et al., 2018; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018; ZAMAN; MECHELEN; BLEUMERS, 2018; GENNARI et al., 2019; BONILLO; MARCO; CEREZO, 2019). Essential skills include User Experience (UX) design skills (e.g., user research, idea generation, rapid prototyping, etc.) and IT skills (e.g., data management, data protection strategies, etc.). Adequate methods and tools can support training those skills with interdisciplinary teams and creators (e.g., designers, developers, engineers, etc). *Human-Centered Design (HCD)* refers to an iterative approach to interactive systems development that involves the human perspective in all stages of the problem-solving process. The HCD stages are namely inspiration, ideation, and implementation (GROUP et al., 2010). The inspiration stage includes performing initial user research (e.g., defining the target audience and eliciting specific user requirements) and seeking existing solutions and inspirational artifacts. The ideation stage covers problem-solving through generating, selecting, and polishing concepts based on user research information and inspirational artifacts. Finally, the implementation stage covers early prototyping of ideas to advanced functional prototypes, considering user evaluation feedback and iterative design cycles. Creators move from inspiration to ideation and implementation, completing one iterative cycle. They keep performing the HCD problem-solving process until final decision-making fully satisfies the stakeholders' needs.

This thesis supports problem-solving and decision-making processes related to hardware–software integration and cybersecurity aspects by intervening in these three HCD stages. Intervention consists of a collection of design tools, supporting problem-solving and decision-making from the early inspiration to advanced implementation and user testing. The motivation is to support creators in overcoming challenges inherent to hardware–software integration, starting from user research to ideation, data collection planning, and rapid prototyping. This thesis also incorporates privacy by design principles across the HCD stages. *Privacy by Design* refers to a list of preventive measures and guidelines to support privacy-related decision-making during the system development process (CAVOUKIAN; POPA, 2016). As part of the privacy by design principles, planning data collection makes it possible to anticipate potential privacy risks and correct any negative impact before they occur. For instance, there are many benefits of collecting PD to support CCI, but creators must first plan all data management behaviors related to each user or system task to ensure they are, in fact, essential and not desirable.

1.2.2 Research Methods and Goals

This thesis applies the *Design Science Methodology (DSM)* to address the following research question. *How can design tools support interdisciplinary teams and creators in training UX design and IT skills related to problem-solving and decision-making during system development?* DSM refers to designing and investigating artifacts in context seeking to improve this context (WIERINGA, 2014). DSM covers three steps in the design cycle: problem investigation, treatment design, and treatment validation. Problem investigation aims to investigate the context defining the stakeholders' needs and goals. In this thesis, the problem investigation defines that the primary stakeholders are creators of different interdisciplinary backgrounds, coming from the CCI research community and industries.

The treatment design aims to select existing artifacts or propose new ones to improve this problem context while addressing the stakeholders' goals. The primary research goal is to facilitate students and professionals seeking more design opportunities while being aware of the potential ethical issues for designing integrated artifacts for children. The approach is supporting them with a collection of design tools intervening in problem-solving and decision-making processes. Thus, one proposes, implements, and evaluates a collection of design tools to improve this research problem context following the HCD perspective. The HCD tools integrate steps from user research, brainstorming sessions, data collection planning, and low to high-fidelity prototyping of integrated CCI artifacts.

Treatment validation distributes tools according to the three HCD stages: inspiration, ideation, and implementation, and integrates data collection planning in all stages supporting meeting privacy by design principles (CAVOUKIAN; POPA, 2016). As part of the engineering cycle, the treatment evaluation implements the HCD tools and evaluates them in a real-world context. This thesis implements seven HCD tools and extensively tests them with interdisciplinary stakeholders in a series of case studies. Also, this research adapts digital versions of the HCD tools to support remote teamwork and education in the face of the social distancing context during the SARS-CoV-2 (COVID-19) pandemic (NICOLA et al., 2020). The specific goals of this research are listed as follows.

- Classify integrated CCI artifacts based on literature and industry items.
- Propose design tools supporting the HCD problem-solving approach for integrated CCI artifacts development.
- Incorporate privacy by design principles supporting decision-making on data management aspects in the HCD stages.
- Evaluate the HCD tools with interdisciplinary stakeholders seeking to incorporate any necessary improvements.
- Adapt the collection of HCD tools to support remote training and learning.

1.3 THESIS PRESENTATION

The remaining contents of this thesis organize as follows.

Chapter 2 Theoretical Background: discusses different HCI paradigms related to integrated CCI artifacts, classifies them according to functional features, and details existing data types within this context. The contents of this chapter are available in two scientific contributions (ALBUQUERQUE; KELNER, 2018; ALBUQUERQUE; KELNER, 2019)

Chapter 3 Related Work: compares literature items on HCD tools for hardware-software integrated systems in CCI and related IoT systems, existing tools and strategies adopted by the CCI industries' professionals, and discusses data privacy risks and proposed solutions from related literature.

Chapter 4 Research Method: details the DSM stages namely *problem investigation*, *treatment design*, *treatment validation*, and *treatment evaluation* (WIERINGA, 2014). The treatment design follows HCD and privacy by design principles while satisfying stakeholders' needs.

Chapter 5 Toy User Interface Toolkit: describes the final version of the proposed HCD tools, including alternative digital versions and remote training strategies for the COVID-19 pandemic context. The contents of this chapter are published in five scientific contributions (ALBUQUERQUE; KELNER, 2019; ALBUQUERQUE; KELNER; HUNG, 2019; ALBUQUERQUE et al., 2020; WHELER et al., 2020; WHELER et al., 2021).

Chapter 6 Evaluation: highlights results from a series of case studies with 255 stakeholders in seven Brazilian, Canadian, and German institutions. Discusses the applicability of HCD tools regarding hardware-software implementation and data security, and stakeholder evaluation strategies. The contents of this chapter are published in six scientific contributions (ALBUQUERQUE; BREYER; KELNER, 2017; ALBUQUERQUE; KELNER, 2019; ALBUQUERQUE; KELNER; HUNG, 2019; ALBUQUERQUE et al., 2020; WHELER et al., 2020; WHELER et al., 2021).

Chapter 7 Thesis Contributions: summarizes this thesis's main contributions on hardware–software integration in CCI, lists the primary scientific contributions (ALBUQUERQUE; KELNER, 2018; ALBUQUERQUE; KELNER, 2019; ALBUQUERQUE; KELNER; HUNG, 2019; ALBUQUERQUE et al., 2020; WHELER et al., 2020; WHELER et al., 2021) and secondary contributions (YANKSON et al., 2019a; ALBUQUERQUE et al., 2020; FANTINATO et al., 2020; MELO et al., 2020), and discusses future works.

2 THEORETICAL BACKGROUND

The present chapter discusses different terminologies and Human-Computer Interaction (HCI) paradigms related to the thesis. The following section classifies existing hardware-software integrated Child-Computer Interaction (CCI) artifacts according to a collection of play and interface features (ALBUQUERQUE; KELNER, 2018). The final section details different data types that these CCI artifacts can collect, classifying them into Personal Data (PD) and non-PD collection (ALBUQUERQUE; KELNER, 2019).

2.1 HARDWARE–SOFTWARE INTEGRATED ARTIFACTS

There is no consensus or definite terminology in the related literature to refer to hardware–software integrated artifacts in CCI. Primarily referred to as *smart toys* (DENNING et al., 2009), different terms also appear such as *connected toys, interactive toys, Toy Computing* (HUNG; RAFFERTY; FANTINATO, 2019), *Internet of Toys* (MASCHERONI; HOLLOWAY, 2019), *Phygital Game Objects* (COULTON, 2015), and so on. The term *smart toys* have long been used in the traditional toy industry to designate electronic-enhanced toys, such as remote-controlled toys. Manufacturers also use the term *smart toys* to refer to traditional toys challenging for kids, such as physical dexterity toys, puzzles, and board games. The term *smart toys* may have grown inadequate to contemplate different integrated CCI artifacts and their many features and computing technologies. The miniaturization and lower costs of processing circuits have contributed to increasing hardware–software integration in CCI (TANG; HUNG; TEWELL, 2015). Several artifacts offer sensory technology and wireless communication features using Bluetooth, Wi-Fi, and Near-Field Communication (NFC), permitting to connect them with devices and accessing online computing services in the cloud (RAFFERTY et al., 2017). A new wave of integrated CCI artifacts also uses Artificial Intelligence (AI)-based technologies to offer more advanced conversation functions by collecting voice and presenting logical reasoning capabilities (MCREYNOLDS et al., 2017).

In the HCI domain, authors have labeled integrated CCI artifacts as Playful User Interfaces (PUI) and Tangible User Interfaces (TUI) (COULTON, 2015; SHAER; HORNECKER, 2010). These artifacts are PUI since they present a playful appearance that engages the user to perform HCI tasks (NIJHOLT, 2014). Concomitantly, they are TUI since the toy components provide a physical form to bits of digital information (ISHII, 2007). Nevertheless, these two HCI paradigms do not adequately contemplate some CCI features, such as promoting physical and social play, and neither PUI nor TUI focus on CCI tasks. Initially, heuristics to introduce playfulness in the user interface design aims to extract features from computer games to make Graphical User Interfaces (GUI) exciting and enjoyable to use (MALONE, 1982). Meanwhile, a TUI refers to a graspable form of interacting with a computer system. Integrated CCI artifacts are not limited to playful physical components acting as interface components, and they can introduce new paradigms to the HCI tasks they promote.

Other HCI domains related to this CCI context include Mixed-Reality (MR) and multimodal interfaces. MR interfaces refer to blending physical and virtual interface components, anywhere between the extent of the reality—virtuality continuum, such as Augmented Reality (AR) interfaces (MILGRAM; KISHINO, 1994). Multimodality refers to interfaces that provide input and output interaction using different sensory channels and feedback modalities (e.g., visual, auditory, and tactile) (TURK, 2014). Also, this CCI cohort merges into the AI and Human-Robot Interaction (HRI) domains. AI technologies in the CCI context include natural language processing, machine learning, information retrieval systems, and robotics (NILSSON, 2014). HRI, more specifically Child-Robot Interaction (cHRI), refers to a multidisciplinary approach to design, implement, and evaluate how robots can interact with and be perceived by children (BELPAEME et al., 2013; BARTNECK et al., 2020).

Companion robots can interact with a child through robot embodiment features (e.g., microphone, speaker, camera, sensors, displays, etc.) and adapt their intelligence and behavior through the perception of specific social cues (e.g., voice commands, gestures, facial expressions, etc.) (BARTNECK; FORLIZZI, 2004). A companion robot's interactive features are set by its physical constraints, influencing how a robot perceives and behaves in the social world (BARTNECK et al., 2020). HRI features such as human-likeness, robot emotion, verbal and non-verbal interaction, and spatial interaction can play significant roles in human perception, trust, and expectations towards companion robots (GOODRICH; SCHULTZ, 2008; DUFFY, 2003; HANCOCK et al., 2011). Children and adults can perceive them as social actors since they represent a physical presence in the interaction environment (BARTNECK et al., 2020). Particularly in CCI, companion robots can assume different roles. They can act as supporting devices to manage play rules, including displaying content or digital information, similar to a companion application running on a smartphone or tablet (HAN et al., 2015). Companion robots can support CCI by acting as active social actors like a co-player or competitive player (DÖNMEZ; BÖREKÇI; GIELEN, 2018). They can also assume a passive social role, such as a guide to the play rules (i.e., the role of an educator or caregiver) or a companion that engages a child during HRI tasks (i.e., the role of a friend) (STAL et al., 2019).

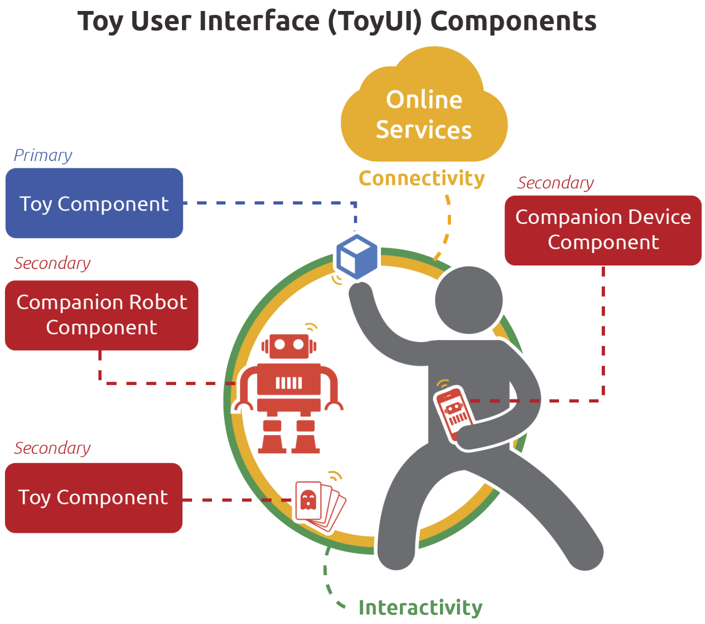
2.2 TOY USER INTERFACES

The setup integration of one or more physical toy components with other hardware or software components constitutes a *Toy User Interface (ToyUI)* setup (ALBUQUERQUE; KELNER, 2018). Aiming to contemplate a broader extent of interface setups and a more comprehensive interaction model that includes HRI features, this thesis refers to integrated CCI artifacts as simply *ToyUI setups*. A ToyUI setup consists of at least one playful physical computing device or peripheral that allows interactivity and connectivity to leverage physical and social play activities to the users. A ToyUI setup can integrate various hardware and software components while exploring different computing technologies. Computing technologies include AR and other MR applications, HRI applications, sensory-based and Internet of Things (IoT) applications, speech recognition and AI applications, and location-based applications (TANG; HUNG; TEWELL, 2015). This definition comes from qualitative content analysis of systematic and industry mappings results, which are fully available in the special issue on *Computing in Smart Toys and Related Internet of Things Applications* in the *Journal of Systems Architecture* (ALBUQUERQUE; KELNER, 2018).

In Figure 1, a general ToyUI setup constitutes at least one primary toy component supporting interactivity with users and integration with secondary components. Primary toy components may appear in various shapes and sizes, such as a plush toy, a doll, a ball, or a wearable gadget. They can use passive technologies (e.g., AR markers) or embed active sensors and actuators (e.g., motion sensors, cameras, microphones, etc.) to collect and manage user information while providing adequate user feedback. A primary toy component can integrate a secondary component to enhance its features, such as enhancing local processing capacity, facilitating hardware and software integration, and providing access to online services like cloud processing and Global Positioning System (GPS) (RAFFERTY et al., 2017). Secondary components are companion device components, companion robot components, and other toy components. Companion device components are smartphones, tablets, personal computers, or game consoles, whereas secondary toy components cover various toy accessories, such as wearables, tokens, and playing cards. A companion robot component is a social robot component that can support performing HRI tasks in the ToyUI setup.

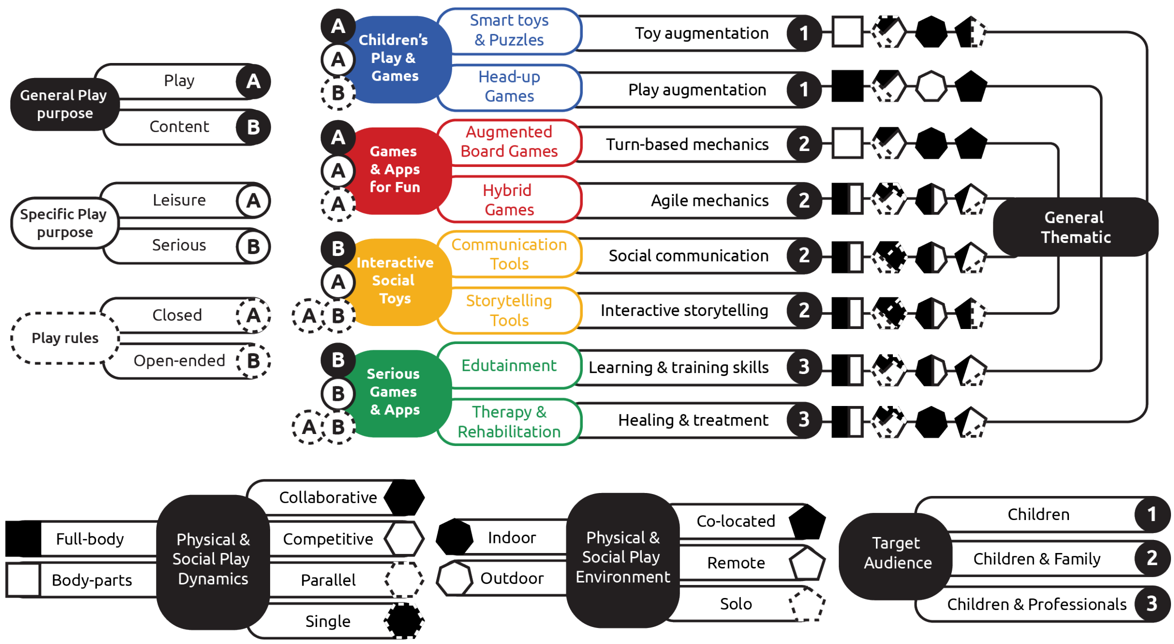
The ToyUI model classifies 22 ToyUI setups into eight genres and four categories, according to the collection of play and interface features presented in Table 1. Categories and genres incorporate different play features (i.e., general and specific play purposes, play rules and dynamics, thematic, target audience, and other physical, social, and environmental aspects). The ToyUI setups differ following the collection of interface features (i.e., types of toy components, connected devices, and peripherals, including their shape, size, symbolic representation, connectivity, and interactivity aspects). Figure 2 shows how the play features distribute the ToyUI setups into categories and genres. Categories encompass general and specific play purposes and the play rules (refer to A and B legends). Genres define the general thematic and target audience (1—3 legends). They can incorporate similar physical and social play dynamics and environment features (shapes legends). Interpreting the first part of this diagram, the Children's Play & Games (CPG) category

Figure 1 – A general interaction model for ToyUI setups.



Source: Author.

Figure 2 – Distribution of play features according to ToyUI categories and genres.



Source: Author.

focus on play-driven (A) and leisure purposes (A) regulating open-ended play rules (B). It divides into two genres: Smart Toys & Puzzles and Head-up Games. The Smart Toys & Puzzles genre includes two general themes: toy augmentation and play augmentation targeting children (1) of different ages. Toy augmentation setups incorporate physical play activities using body parts (square) to promote competitive, parallel, and single play dynamics (hexagon), located indoors (octagon) in co-located or solo social environments.

Tables 2—9 describe the 22 ToyUI setups and their interface features.

Table 1 – Collection of play and interface features to classify ToyUI setups.

PLAY FEATURES	**CLASSIFICATION OPTIONS**
General play purpose	Play or Content
Specific play purpose	Leisure or Serious
Play rules	Closed play or Open-ended play
Target audience	Children, Children & Family, or Children & Professionals
General thematic	Toy augmentation, Play augmentation, Turn-based mechanics, Agile mechanics, Social communication, Interactive storytelling, Learning & training skills, or Healing & treatment
Physical play dynamics	Full-body or Body-parts
Social play dynamics	Parallel, Collaborative, Competitive, or Single
Physical play environment	Indoor or Outdoor
Social play environment	Co-located, Remote, or Solo
INTERFACE FEATURES	**CLASSIFICATION OPTIONS**
Primary component	Passive or Active
Secondary components	Device or Peripheral
Interactivity	ToyUI-to-ToyUI, ToyUI-to-Player, or Player-to-Player
Connectivity	MR, Sensory, or IoT
Shape	Handheld, Wearable, or Playground
Size	Small, Medium, or Large
Symbolic representation	Character, Object or non-Symbolic

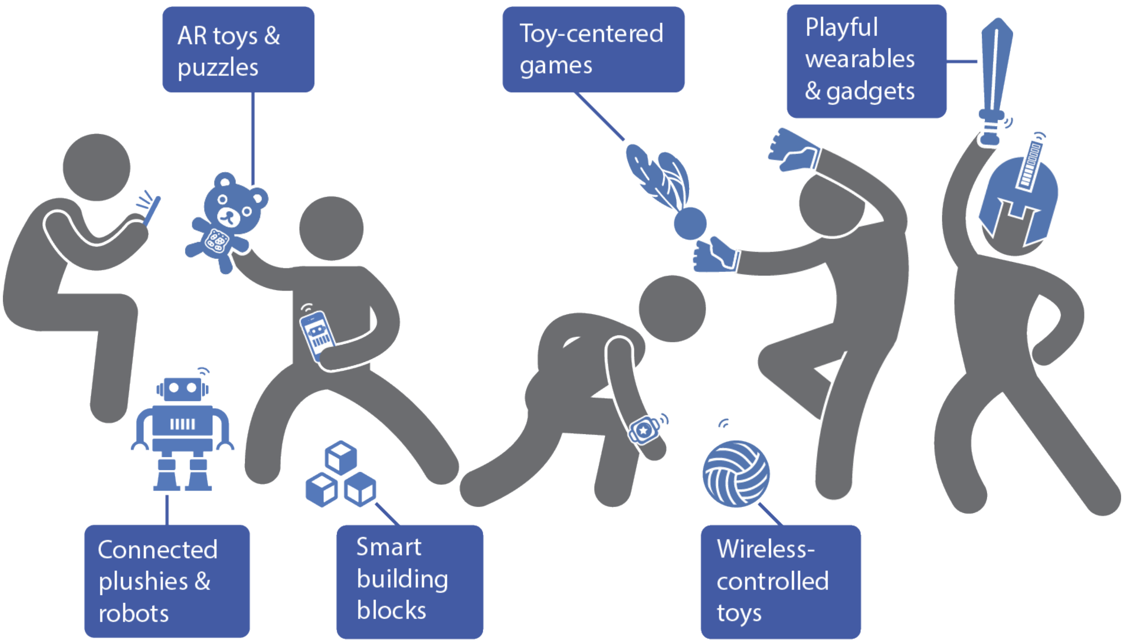
Source: Author.

2.2.1 Children's Play & Games

The traditional toy industry began to employ CCI technologies in toy design to react to the increasing popularity of digital games and consumer robotics products (DHAR; WU, 2015). Children are continuously exposed to digital stimuli since they are in touch with many CCI artifacts in their daily lives. The toy industry is gradually adapting to these new marketing challenges while seeking professional experience designing MR play experiences (TYNI; KULTIMA, 2016). As a result, many ToyUI setups still offer traditional social and physical play activities using toy components like plushies, puzzles, building blocks, and remote-controlled cars (ZAMAN; MECHELEN; BLEUMERS, 2018; HELJAKKA; IHAMäKI, 2019; YANG; DRUGA, 2019; CROVARI et al., 2019; HO et al., 2019).

The *CPG* category introduces play-driven ToyUI setups that resemble traditional toys and play activities, but enhanced through MR technologies and open-ended play rules. Open-ended play activities focus on partially regulating play rules, including data collection and data processing using the ToyUI components (SOUTE; MARKOPOULOS; MAGIELSE, 2010; LIANG; KUO; CHEN, 2016). Sometimes, these ToyUI setups timidly use the innovative potential of new CCI technologies and offer solutions that can work well "offline" (ANTLE; WANG, 2013). Many of them manage to preserve the qualities of open-ended play experiences by stimulating children's imagination during play (SOUTE; LAGERSTRÖM; MARKOPOULOS, 2013; PIJNAPPEL; MUELLER, 2014). Figure 3 shows an infographic representing six ToyUI setups, and Tables 2 and 3 distribute them into two genres: *Smart Toys & Puzzles* and *Head-Up Games*.

Figure 3 – ToyUI setups of the CPG category



Source: Author.

The *Smart Toys & Puzzles* genre covers ToyUI setups that present little interference in the specific play purposes while providing feedback to intangible play experiences, such as pretend to play or imaginative play experiences (PIJNAPPEL; MUELLER, 2014; SEEHRA et al., 2015; CROVARI et al., 2019). This genre incorporates various toy components that support ToyUI-to-ToyUI interactivity. For example, baby dolls *Maya* and *Mia* (Spin Master, 2021) mix traditional and enhanced play using a combination of embedded motors, sensors, lights, sounds, and contactless identification. The play interaction focuses on feeding the baby doll with secondary toy components: a spoon, a food tray, and a baby bottle. A child can use the spoon to mix different combinations in the food tray. Then, the baby doll reacts to the food "taste," emitting sounds and facial expressions. Facial expressions consist of a combination of mouth, eyes, and tongue movements. The child can also use the baby bottle to feed the doll or turn it into a pacifier to help the doll fall asleep.

Other examples are toy drones controlled by companion devices like *Sky Viper* (Sky Rocket, 2021) and modular blocks able to sense one another combining passive technolo-

Table 2 – Smart Toys & Puzzles setups and references.

ToyUI SETUP	**SMART TOYS & PUZZLES GENRE**
AR Toys & Puzzles	The setup uses AR resources to overlap digital content on the primary toy component or to regulate play dynamics in real-time (e.g., *Mapology* (ImagiMake, 2021), *JigPix* (Commonwealth Toy & Novelty Co., 2021), *Ocean Pets* and *Cube-Tastic* (Pai Technology, 2021), *ARIA's Adventures* and *Upshot* (Odyssey Toys, 2021), and *Orboot* (PlayShifu, 2021)). They can also support playing in offline settings (BANG et al., 2010; ANTLE; WANG, 2013).
Connected Plushies & Robots	The setup focuses on pretend play and other free-play activities offering interactive features, such as sounds, lights, and motion (e.g., *Cry Babies* and *Club Petz* (IMC Toys, 2021), *Party Pets, Cute Cuis,* and *Sprint* (Eolo, 2021), *Fart Ninjas* and *Bright Fairy Friends* (Funrise, 2021), and *Care Bears* (Basic Fun!, 2021)). Children can play with the primary toy component independently, using secondary toy components, or connected to companion devices (ABEELE; ZAMAN; ABEELE, 2008; KOZIMA; MICHALOWSKI; NAKAGAWA, 2009; GOMES et al., 2011; AVRAHAMI; WOBBROCK; IZADI, 2011; COONEY et al., 2011; SUGIURA et al., 2012; NIIYAMA et al., 2015; SEEHRA et al., 2015; CROVARI et al., 2019; HO et al., 2019; HELJAKKA; IHAMäKI, 2019; ALBUQUERQUE; KELNER, 2019).
Smart Building Blocks	The setup consists of attachable modular primary toy components able to sense one another (e.g., *Robo Wunderkind* (Robo Wunderkind, 2021), *Qboidz* (Engino, 2021), *Circuit Blox* (E-Blox, 2021), *Light Stax* (The Lazy Dog Co., 2021), and *Hi-Tech Magformers* (Magformers, 2021)). Blocks can connect to companion devices to guide the player or to customize play contents (PARKES; RAFFLE; ISHII, 2008; WELLER; DO; GROSS, 2008; JACOBY et al., 2009; HALSKOV; DALSGAARD; STOLZE, 2014; YANG; DRUGA, 2019).
Wireless Controlled Toys	The setup uses wireless protocols to control the primary toy component's features through secondary components, like other toys, wearables, or companion devices (e.g., *Optimus Prime* (Robosen Robotics, 2021), *Overdrive* (Digital Dream Labs, 2021), *E-Z App* (Bachmann Trains, 2021), *Go Go Bird* (Zing, 2021), *MoBots* (HexBug, 2021), and *RC App Driver* (New Bright, 2021)) (DANG; ANDRE, 2013; DESAI; MCCANN; COROS, 2018; ZAMAN; MECHELEN; BLEUMERS, 2018).

Source: Author.

gies (conductive materials) and active technologies (capacitive touch sensors and contactless identification) (PARKES; RAFFLE; ISHII, 2008; YANG; DRUGA, 2019). Many ToyUI setups can also support play activities that work with or without technological assistance. A jigsaw puzzle system composed of a large Infrared (IR) tabletop and AR-marked puzzle pieces provides feedback to player's actions (e.g., feedback on wrong or correct positioning of the puzzle pieces on top of the tabletop) (ANTLE; WANG, 2013). Likewise, the *Osmo* AR platform (Tangible Play, 2021) offers a physical tangram puzzle system that uses color feature detection to regulate similar play dynamics in a companion application. In both situations, the ToyUI setup can support play without technological enhancement.

Table 3 – Head-up games setups and references.

ToyUI SETUP	HEAD-UP GAMES GENRE
Toy-Centered Games	The setup focuses on a primary toy component that can fully or partially regulate a set of open-ended play rules and dynamics (e.g., *Hide & Seek Pals* (R&R Games Incorporated, 2021), *Slider Disc* (Eolo, 2021), *Talkin' Sportz, Egg Toss,* and *Bubble Biters* (Move-2-Play, 2021), *Hovering Soccer Ball* (Odyssey Toys, 2021), and *Rubik's Revolution* (Super Impulse, 2021)) (BAKKER; MARKOPOULOS; KORT, 2008; HENDRIX et al., 2008; HUYNH et al., 2009; BEKKER; STURM; EGGEN, 2010; FABER, ; SHEN; MAZALEK, 2010; FOGTMANN, 2011; MARTINOIA; CALANDRIELLO; BONARINI, 2013; PIJNAPPEL; MUELLER, 2014; ALBUQUERQUE; KELNER, 2019; ALBUQUERQUE et al., 2020).
Playful Wearables & Gadgets	The setup mixes wireless connectivity, wearable technology, and biosensors to allow embodied physical exertion and open-ended play (e.g., *Dojo Battle* (MGA Entertainment, 2021), *Capture the Flag – Redux* (Starlux Games, 2021), *Wow Tech IR Laser Tag* (NKoK, 2021), *Ben 10 Omnitrix* (Playmates Toys, 2021)) (HENDRIX et al., 2008; SOUTE; MARKOPOULOS; MAGIELSE, 2010; SOUTE; LAGERSTRÖM; MARKOPOULOS, 2013; SEGURA et al., 2013; LIANG; KUO; CHEN, 2016; ALBUQUERQUE et al., 2020).

Source: Author.

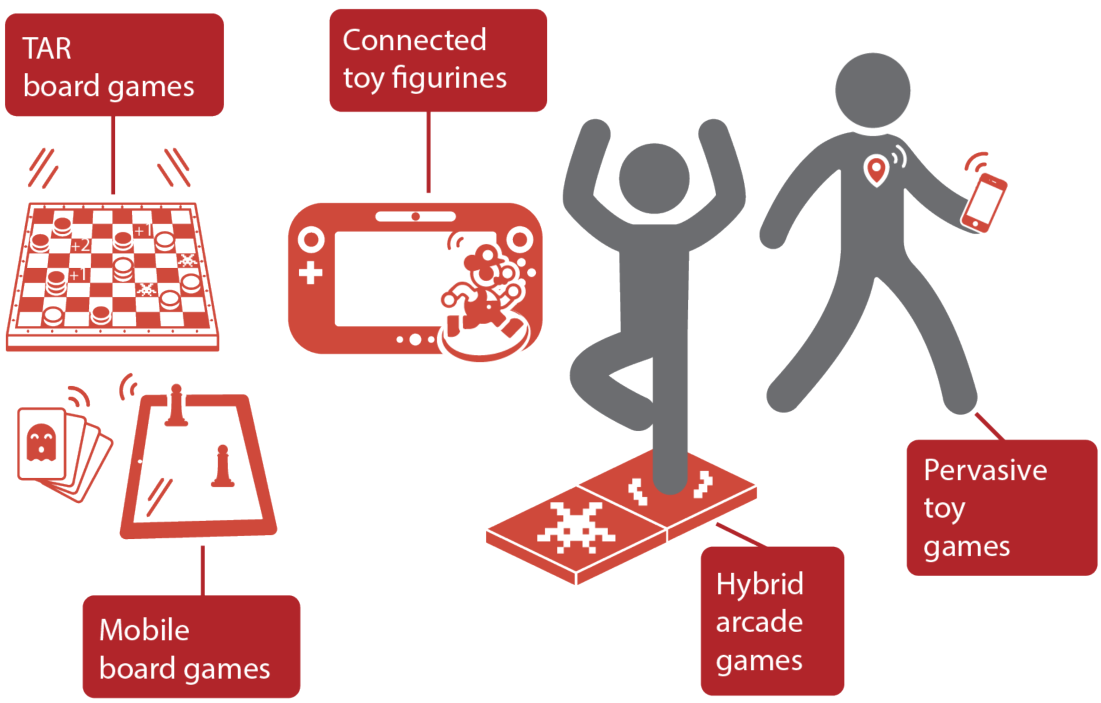
The *Head-Up Games* genre recalls traditional children's open-ended play activities like *tag* and *hide-and-seek*. These ToyUI setups may require large indoor spaces or outdoor environments to enable embodied interplays and physical exertion (PIJNAPPEL; MUELLER, 2014). For example, a ToyUI setup introduces a large lighthouse-toy embedded with a presence sensor, enabling it to detect the player's presence surrounding it (BAKKER; MARKOPOULOS; KORT, 2008). Children collaborate in teams by collecting treasures (plastic coins) back to their pirate ships (circles on the floor) without been exposed to the rotating detection field (the lighthouse's lights). The primary toy component regulates the player detection rule for winning or losing conditions automatically while children regulate other play dynamics such as team composition, number of rewards, and scores.

These ToyUI setups can also support editing the open-ended play rules to generate new play modalities based on embedded sensors' continuous feedback (LIANG; KUO; CHEN, 2016; ALBUQUERQUE et al., 2020). Light-up toy components like *NightZone* (Toy Smith, 2021) and *Redux* (Starlux Games, 2021) can be placed freely in the play environment (e.g., on the floor, in a tree, hidden under a chair, etc.). The primary toy components (balls, sticks, or tokens) provide continuous feedback to the player through different light colors. Secondary wearable components (wristbands, belts, or place holders) allow individual (player) and collective (team) identification. Children can customize open-ended play rules by assigning teams using the light colors and adjusting the distance between toy components in the play environment to increase or decrease play challenges.

2.2.2 Games & Applications for Fun

The *Games & Applications for Fun (GAF)* category brings ToyUI setups that promote play-driven and leisure activities through a set of closed play rules. Closed play rules incorporate game-like dynamics, such as establishing a game state machine, level design, tracking player performance, and player progression (SALEN; TEKINBAŞ; ZIMMERMAN, 2004). These ToyUI setups explore social play dynamics like competition and collaboration among players and teams, and physical play dynamics can vary from manipulating pieces and tokens to full embodied interaction (MORA; LORETO; DIVITINI, 2016; BONILLO; MARCO; CEREZO, 2019). The GAF category comprises items inspired by the game industry, distinguish between physical and virtual components more clearly (SAJJADI et al., 2014; MERRITT et al., 2017). Figure 4 illustrates five types of ToyUI setups, and Tables 4 and 5 distribute them in two genres, the first resembling traditional physical card and board games (e.g., *Solitaire* and chess). The second incorporates agile features mostly present in digital games (e.g., mobile games and console games).

Figure 4 – ToyUI setups of the GAF category



Source: Author.

First, the *Augmented Board Games* genre introduces turn-based game mechanics and ToyUI components regulating closed game rules, dynamic events, and digital content. This genre combines physical or digital game boards and tokens (e.g., figurines, playing cards, etc.), using active or passive technologies. ToyUI setups differ by technology features, such as using mobile devices (MORA; LORETO; DIVITINI, 2016) or other tangible and AR resources to bring game objects to life (MIRONCIKA et al., 2018). For instance, *NKVision*

Table 4 – Augmented board games setups and references.

ToyUI SETUP	AUGMENTED BOARD GAMES GENRE
TAR Board Games	The setup uses toy components or AR resources to bring the toy components to life, such as overlapping digital content, regulating play rules, or triggering unpredictable events (e.g., *Monopoly Super Banking* and *Speech Breaker* (Hasbro, 2021), *Hologrid Monster Battle* (HappyGiant and Tippett Studio, 2021), *Scrib Maze Race* (OwiKit Robotics, 2021), and *UNO Attack* (Mattel, 2021)) (HEIJBOER; HOVEN, 2008; XU et al., 2008; HINSKE; LANGHEINRICH, 2009; MARCO; CEREZO; BALDASSARRI, 2012; MIRONCIKA et al., 2018).
Mobile Board Games	The setup uses companion applications to regulate play rules, dynamics, data collection, and data processing (e.g., *Word of Yo-Ho* (Volumique, 2021), *Shoppin' Blowout* (Komarc Games, 2021), *Camera Roll* (Endless Games, 2021), *Space Hawk* (Ravensburger, 2021), and *What's that smell?* (Yulu Toys, 2021)). The mobile display can fully or partially replace physical game objects (AVRAHAMI; WOBBROCK; IZADI, 2011; PILLIAS; ROBERT-BOUCHARD; LEVIEUX, 2014; SAJJADI et al., 2014; MORA; LORETO; DIVITINI, 2016).

Source: Author.

is an IR tabletop display that allows recognizing fiducial markers attached to the bottom of passive tokens, enabling it to distinguish them individually and estimate their relative position on the game board (MARCO; CEREZO; BALDASSARRI, 2012). Alternatives for detecting passive tokens are digital cameras combined with displays like projectors or Head-Mounted Displays (HMD) (HINSKE; LANGHEINRICH, 2009).

NFC is an alternative to support the tangible interaction of active tokens, such as in the tangible platform *Sifteo Cubes* (MERRILL; SUN; KALANITHI, 2012). *Sifteo Cubes* are modular cubic touchscreen displays that can transfer data for each other and support direct manipulation and natural gesture interactions (e.g., shaking and flipping the cubes) (PILLIAS; ROBERT-BOUCHARD; LEVIEUX, 2014; SAJJADI et al., 2014). Touchscreen displays can also use conductive materials to recognize passive tokens through triangulation algorithms (e.g., *TapTop* (Blok Party, 2021) (FUCCIO; SIANO; MARCO, 2017; APPERT et al., 2018). Mobile applications like *Shuffle* (Cartamundi, 2021) augments physical play by introducing additional digital content (e.g., digital playing cards), and providing play instructions and rules. In another example, the company *Virsix Games* (2021) uses the *Amazon Echo* (Amazon, 2021) to integrate audio and AI contents using *Alexa's* voice and speech processing services.

In contrast, the *Hybrid Games* genre introduces agile game mechanics combining physical toy components and closed play rules inspired by the digital games industry. In these ToyUI setups, toy components embody the role of game objects, allowing them to interact with other (physical or virtual) game objects and update their game state during play. Setup examples include toy figurines on a tabletop surface or connected to vertical displays, such as television, tablets, and monitor displays (e.g.,*Beasts of Balance* (Beasts

Table 5 – Hybrid games setups and references.

ToyUI SETUP	**HYBRID GAMES GENRE**
Connected Toy Figurines	The setup uses handheld toy components (characters and objects) to interact with companion devices (e.g., *Tap Maste*r (Smart Lumies, 2021), *Tori* (Bandai Namco, 2021), *Klikbot* (Zing, 2021), *Hot Wheels ID* (Mattel, 2021), *Amiibo* (Nintendo, 2021), and *Oniri Islands* (Tourmaline Studio, 2021)). Toy components can have a fixed shape and attach/swap with other pieces to update its data state (NIELSEN et al., 2009; AVRAHAMI; WOBBROCK; IZADI, 2011; SLYPER; POUPYREV; HODGINS, 2010; KATSUMOTO; TOKUHISA; INAKAGE, 2013; DANG; ANDRE, 2013; ALBUQUERQUE; BREYER; KELNER, 2017; ZAMAN; MECHELEN; BLEUMERS, 2018; CHEN et al., 2019; SOYSA; MAHMUD, 2019; ALBUQUERQUE et al., 2020).
Hybrid Arcade Games	The setup consists of indoor or outdoor playgrounds supporting tracking the player's performance using various components and providing continuous user feedback (e.g., *Projecteur de danse* (Carrera Toys, 2021), *Nintendo Labo* (Nintendo, 2021), and *MIP Arcade* (WowWee, 2021)) (TEDJOKUSUMO; ZHOU; WINKLER, 2009; CHEOK, 2010; YAO et al., 2011; MUELLER et al., 2014; TODI et al., 2016; ALTIMIRA et al., 2016; LIANG; KUO; CHEN, 2016; SHAPIRA; AMORES; BENAVIDES, 2016; ALBUQUERQUE; BREYER; KELNER, 2017; SHAKERI et al., 2017; DELDEN et al., 2017; BONILLO; MARCO; CEREZO, 2019).
Pervasive Toy Games	The setup combines companion devices and primary toy components to support pervasive play (e.g., *Pokemon GO Plus* (Nintendo, 2021), *LilBytes* (LilBytes, 2021), *Tobi* (MGA Entertainment, 2021), *Color BlastAR* (HitPoint, 2021), *Wristworld* (Crypton Future Media, 2021), *Fungisaurs* (Fungisaurs, 2021)). It can also combine AR resources and wearable technology with location services to improve physical exertion and stimulate social interaction (WILLIS; POUPYREV; SHIRATORI, 2011; FURIÓ et al., 2013; MERRITT et al., 2017; DELPRINO et al., 2018).

Source: Author.

of Balance, 2021) and *Amiibo*). These ToyUI setups can also integrate digital cameras to support creating a computer vision detection field. For instance, *Cubica* uses a webcam facing down attached to a monitor display, creating a detection field aiming at the player's hands (ALBUQUERQUE; BREYER; KELNER, 2017). Players manipulate the primary toy components (two Rubik's cubes), and an image processing algorithm detects color features to validate the game actions. Similar technologies appear in the *Osmo* platform and *Portico* platform (AVRAHAMI; WOBBROCK; IZADI, 2011). This genre can also explore embodied interaction by combining different sensory technologies, such as depth sensors and game controllers (YAO et al., 2011). More complex setups can mix various ToyUI components to support physical and social play, such as wearable technology and large physical installations (CHEOK, 2010; BONILLO; MARCO; CEREZO, 2019).

Pervasive play can promote outdoor activities using GPS information (GUO et al., 2010; VALENTE; FEIJÓ; LEITE, 2017; DELPRINO et al., 2018) or connecting toy components to a local network (MERRITT et al., 2017). GPS enables estimating a child's real-time location, including his/her geolocation preferences (e.g., the child's home address and recurrent locations), making it essential to secure appropriate system infrastructure for PD protection (SHASHA et al., 2018). The *Pokemon GO* phenomenon, for example, adds other potential risks to a child's safety since several urban incidents may occur on players sharing attention on the mobile screen and surroundings (POURCHON et al., 2017). *Nintendo* released the toy component *Pokemon GO Plus* aiming to reduce playing time interacting with the screen. The device resembles the classic *Pokeball*, providing information and access to game information, such as nearby game spots, characters, and items, and integrating content across multiple platforms (e.g., mobile application and compatible game consoles *Nintendo Switch* and *New Nintendo 3DS XL* (Nintendo, 2021)).

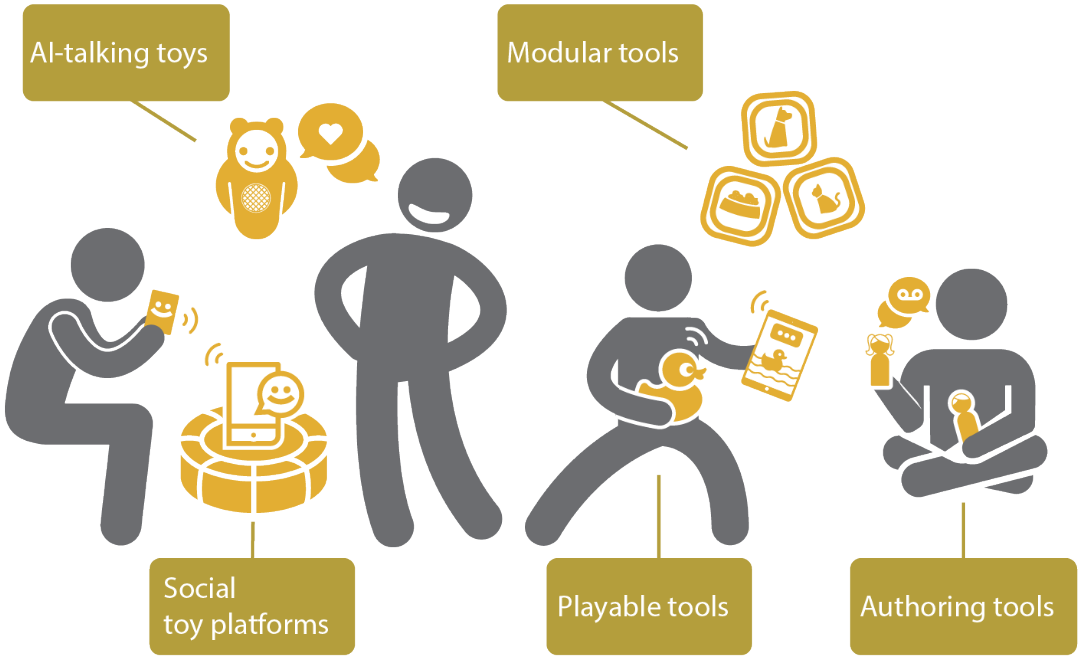
2.2.3 Interactive Social Toys

In Figure 5, the *Interactive Social Toys (IST)* category comprises content-driven ToyUI setups focused on promoting leisure while supporting social interaction among participants and ToyUI components. Tables 6 and 7 distribute them in two genres: *Communication Tools* and *Storytelling Tools*. These ToyUI setups either promote the generation of new social content (by stimulating conversational topics or supporting creative storytelling) or promote decision-making of existing social content (by providing a preset of talking lines and responses or narrative elements like characters, timelines, and key plot events). They can collect PD like text, voice, and video to support essential CCI tasks and may store PD for improving content and online services. For example, AI-based services may involve data quality assessment to improve natural language processing services — a practice that consumers have been questioning due to many privacy risks associated with such a strategy (MCREYNOLDS et al., 2017).

The *Communication Tools* genre supports social interaction promoting real-time or parallel communication, focusing on the social toy component itself or mediating social CCI tasks between children, parents, siblings, and friends. The *AI Talking Toys* setup, for instance, uses speech recognition and AI resources to hold a conversation with a child by listening, recording, and processing their voices. Often this ToyUI setup requires a connection with companion devices to increase computing capacity and share data processing features locally or online (RAFFERTY et al., 2017; MEGHDARI et al., 2018; DÖNMEZ; BÖREKÇI; GIELEN, 2018; STAL et al., 2019). Ideally, the entire communication within these terminals and online services should be fully encrypted and require authentication to access user data, but multiple industry items were discontinued due to many privacy-related issues they introduced (e.g., *Hello Barbie* (Mattel, 2015—20219) and *Dino* (Cognitoys, 2015—2019)) (MCREYNOLDS et al., 2017).

In contrast, other communication tools can establish remote or co-located communication between individuals using multimedia inputs and outputs, such as text, voice, video,

Figure 5 – ToyUI setups of the IST category



Source: Author.

Table 6 – Communication tools setups and references.

ToyUI SETUP	**COMMUNICATION TOOLS GENRE**
AI Talking Toys	The setup supports speech recognition and uses AI resources to promote reasoning-based dialogue between the child and the primary toy component or companion robot component (e.g., *Little Sophia* (Hanson Robotics, 2021), *Miko 2* (Emotix, 2021), *Fuzzible Friends* (Jazwares, 2021), and *Call Me Chloe* (Hunter Products, 2021)) (NAKADAI et al., 2015; VALADÃO et al., 2017; DÖNMEZ; BÖREKÇI; GIELEN, 2018; MEGHDARI et al., 2018; WILLIAMS; PARK; BREAZEAL, 2019; FISICARO et al., 2019).
Social Toy-Platforms	The setup mediates real-time or parallel communication between two or more users by setting up a chat room using secondary peripherals like microphones, speakers, digital cameras, projectors, and other displays (e.g., *Avakai* (Vakai, 2021)) (YAROSH et al., 2009; FREED et al., 2010; YAROSH; INKPEN; BRUSH, 2010; SAKAMOTO; ALEXANDROVA; NAKAJIMA, 2016; MELONIO; RIZVI, 2016; TALIB et al., 2018; NUNEZ et al., 2018).

Source: Author.

and animations (MELONIO; RIZVI, 2016; TALIB et al., 2018; NUNEZ et al., 2018), or funny sounds like the wooden toys *Avakai*. *Social Toy-Platforms* like the *Video Playdate* platform overlap two remote physical spaces using display projectors so that siblings can play with their toys and share them as virtual replicas (YAROSH; INKPEN; BRUSH, 2010). Similarly, in *ShareTable*, a child and his/her parents can share two mixed reality tables overlapped by projectors, enabling them to play and do school homework together (YAROSH et al.,

Table 7 – Storytelling tools setups and references.

ToyUI SETUP	STORYTELLING TOOLS GENRE
Playable Tools	The setup enables reproducing predefined stories by interacting with characters and other plot elements while following an interactive timeline (e.g., *See, Hear, and Read* (Bendon, 2021), *Baby Einsten Sound Books* (Phoenix International Publications, 2021), and *Appy Kids* (Growl Media, 2021)). Users can make decisions on these stories by selecting different key plots (HORNECKER; DÜNSER, 2009; GARZOTTO; BORDOGNA, 2010; SHEN; MAZALEK, 2010; OFFERMANS; HU, 2013; NAKEVSKA et al., 2017; HAN et al., 2015; LIANG; KUO; CHEN, 2016; SPIEL; MAKHAEVA; FRAUENBERGER, 2016; PATEL; SCHNÄDELBACH; KOLEVA, 2018; HONAUER; MOORTHY; HORNECKER, 2019; FISICARO et al., 2019; STAL et al., 2019).
Modular Tools	The setup offers predefined plot elements to build interactive timelines using modular toys (e.g., *Pick & Play* (Grinsire, 2021), and *Mirari* (Play Monster, 2021)). Like block coding, modules are organized into classes to support their combinations, including programming or editing behaviors (ZHOU et al., 2008; HUNTER; KALANITHI; MERRILL, 2010; OH et al., 2013; WANG; HE; DOU, 2014; BAI; BLACKWELL; COULOURIS, 2015; STAL et al., 2019).
Authoring Tools	The setup supports users in creating new stories by recording or editing plot elements based on the input of contents like audio, text, and digital media (e.g., *Bloxels* (Pixel Press Technology, 2021), *DoodleMatic* (Tink Digital Inc, 2021), and *My Audio Pet* (Jakab Solutions, 2021)) (VAUCELLE; ISHII, 2008; FARR et al., 2010; MENDES; ROMÃO, 2011; OH et al., 2013; SPIEL; MAKHAEVA; FRAUENBERGER, 2016).

Source: Author.

2009). Social toy platform setups can potentially support overcoming the impacts of social isolation in children and adolescents during the COVID-19, including supporting remote learning and homeschooling activities (KASSAB; MAZZARA, 2019; TAVAKOLI; CARRIERE; TORABI, 2020; VINER et al., 2020; LOADES et al., 2020)

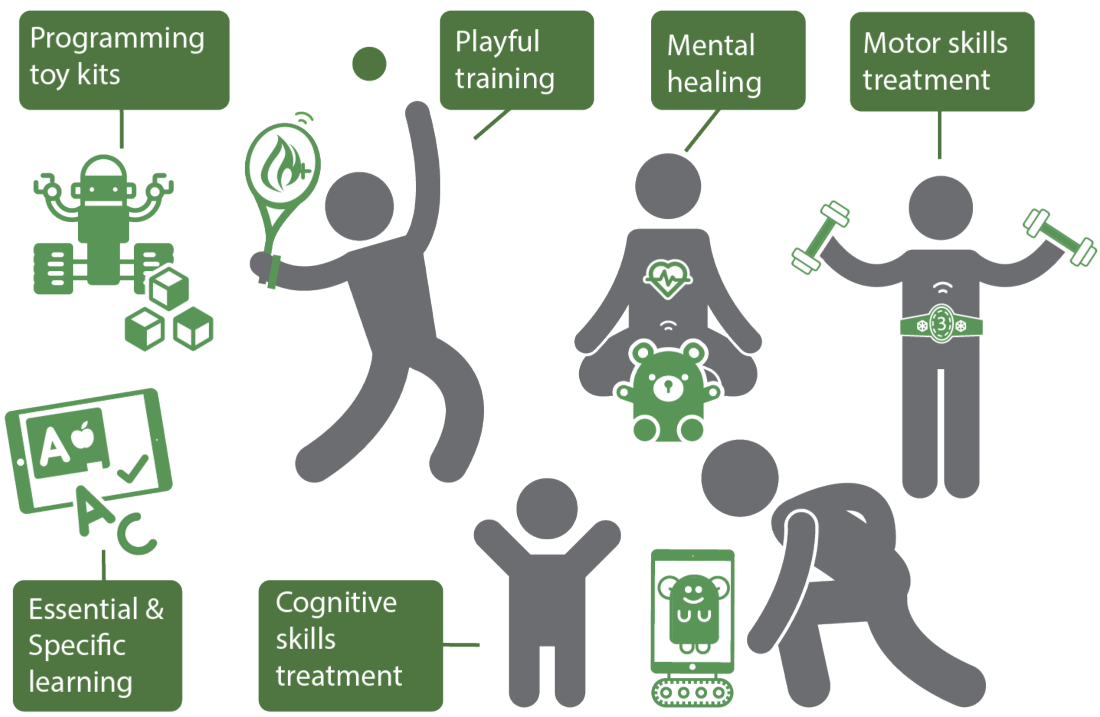
The *Storytelling Tools* genre comprises interface features that support the creation or decision-making of narrative contents. For instance, *PuzzleTale* supports decision-making by detecting puzzle pieces on the top of an IR tabletop, and the order of selected tabletop constraints results in different story versions (SHEN; MAZALEK, 2010). Regularly, this genre introduces open-ended or predefined narrative components to represent characters and other plot elements. Like digital games, the child can interfere in the character's journey by selecting, combining, or editing these narrative components (HONAUER; MOORTHY; HORNECKER, 2019; FISICARO et al., 2019; STAL et al., 2019).

This genre includes three ToyUI setups, namely *Playable tools, Modular tools,* and *Authoring tools*, and often the same ToyUI setup can support parallel features. In a study, authors tested different storytelling setups using the companion robot *Cozmo* (Anki, 2018 – Digital Dream Lab, 2021) and toy figurines (STAL et al., 2019). This ToyUI setup transitioned from playable to modular, and authoring tools, experimenting with different companion robot roles, such as passive and active roles during storytelling. Similarly, *StoryCube* mixes *modular* and *authoring* features, allowing the child to select plot elements (e.g., sky, ground, and objects) using a cubic toy component made of LEGO bricks (WANG; HE; DOU, 2014).

2.2.4 Serious Games & Applications

The *Serious Games & Applications (SGA)* category promotes content-driven play experiences that serve a range of operative purposes (e.g., learning and therapy). These ToyUI setups, in Figure 6, incorporate interface features similar to all three previous categories but present significant differences in their operative purposes and data collection usage. They can train an individual's physical and social abilities and sometimes support social inclusion by targeting multiple audiences (e.g., children, parents, elderly, individuals with cognitive disabilities or physical impairments, educators, therapists, etc.) (SOYSA; MAHMUD, 2019). The SGA category divides into two comprehensive genres: *Edutainment* and *Therapy & Rehabilitation*. Tables 8 and 9 show the diverse collection of ToyUI setups of this category, namely, *Essential and Specific Learning, Programming Toy Kits, Playful Training, Cognitive Skills Treatment, Motor Skills Treatment,* and *Mental Healing*.

Figure 6 – ToyUI setups of the SGA category



Source: Author.

The *Edutainment* genre introduces ToyUI setups dedicated to supporting theoretical and practical learning topics. Theoretical learning topics may include everything from

Table 8 – Edutainment setups and references.

ToyUI SETUP	EDUTAINMENT GENRE
Programming Toy-Kits	The setup focuses on training computer coding skills using the primary toy component or the connected components (e.g., *Mazzy* and *Woki* (Blue Rocket Toys, 2021), *Botley* (Learning Resources, 2021), *Artie 3000* (Educational Insights, 2021), *Vex Series* (Vex Robotics, 2021), *Dash* and *Cue* (Wonder Workshop, 2021), *Vector* and *Cozmo* (Digital Dream Lab, 2021)). The level of coding skills vary by age group/target audience (SCHARF; WINKLER; HERCZEG, 2008; HORN et al., 2009; WANG et al., 2016; BERGSMARK; FERNAEUS, 2016; KAZEMITABAAR et al., 2017; MEADTHAISONG; MEADTHAISONG, 2018; CANO et al., 2018; WILLIAMS; PARK; BREAZEAL, 2019).
Essential & Specific Learning	The setup supports content-driven education through play, exploring various theoretical learning topics (e.g., *Marbotic* (Marbotic, 2021), *GeoSafari Globe* (Educational Insights, 2020), *Mindlabs* (HitPoint, 2020), and *Magik Play* (Magikbee, 2021)) (WAKKARY et al., 2009; HENGEVELD et al., 2009; HUNTER; KALANITHI; MERRILL, 2010; SPEELPENNING et al., 2011; ANTLE; WISE; NIELSEN, 2011; TSONG; CHONG; SAMSUDIN, 2012; FURIÓ et al., 2013; GNOLI et al., 2014; HAFIDH et al., 2014; KUBICKI et al., 2015; YANNIER et al., 2016; OKERLUND et al., 2016; ZIDIANAKIS et al., 2016; KOBEISSI et al., 2017; JAFRI; ALJUHANI; ALI, 2015; MARICHAL et al., 2017; ALAKÄRPPÄ et al., 2017; FAN et al., 2017; ANDERSON et al., 2018; LEE; KIM, 2018; CANO et al., 2018; EKIN; ÇAĞILTAY; KARASU, 2018; SOYSA; MAHMUD, 2019; BONILLO et al., 2019; KIM; POSLAD, 2019; WANG et al., 2020).
Playful Training	The setup supports training abilities that combine physical and mental tasks (e.g., *Disney Magic Timer* (HitPoint, 2020), *ROX Pro* (A-Champs, 2021), *ColorXplore* (Mozbii, 2021), *PlayBrush* (Play Brush, 2021), *Learn with Lights* (Hape Wooden Toys, 2021), and *Ok to Wake* (Play Monster, 2021)). The primary toy component varies according to the training subject, and it often provides biofeedback to the users (FOGTMANN, 2011; YAMABE; NAKAJIMA, 2013; JENSEN; RASMUSSEN; GRØNBÆK, 2013; GEURTS et al., 2014; ANDERSON et al., 2018; MEADTHAISONG; MEADTHAISONG, 2018; KARA; CAGILTAY, 2020).

Source: Author.

essential learning to specific topics, such as language, Science, Technology, Engineering, and Mathematics (STEM), history, ecology, sustainability, and so on (KIM; POSLAD, 2019; WANG et al., 2020). Practical learning examples are training musical instruments, sports, coding skills, sewing, drawing, cooking, and so on (MEADTHAISONG; MEADTHAISONG, 2018; KARA; CAGILTAY, 2020). *Programming Toy Kits* like *Sphero* and *Littlebits* (Sphero, 2021) offer companion devices components to support coding lessons. *Ozobot* (Ozobot, 2021) also allows coding through color tracing and examples like *Cubetto* (Primo Toys, 2021) and *Coding Critters* (Learning Resources, 2021) use tangible resources to support coding lessons. *Cubetto* is a wooden toy component that kids can code navigation functions using a set of geometric forms representing them (e.g., a circle means "go," square means

Table 9 – Therapy & Rehabilitation setups and references.

ToyUI SETUP	**THERAPY & REHABILITATION GENRE**
Cognitive Skills Treatment	The setup supports the training of cognitive and social abilities of individuals (e.g., *WOZ Teacher's Aide* (Movia Robotics, 2021) and *Leka* (APF France Handicap, 2021)). The target audience includes autistic children and other neurodivergent individuals (BROK; BARAKOVA, 2010; SPIEL; MAKHAEVA; FRAUENBERGER, 2016; GARZOTTO; GELSOMINI; KINOE, 2017; BONILLO et al., 2019; VALADÃO et al., 2017; AN et al., 2018; TALIB et al., 2018; ALHADDAD et al., 2018; NUNEZ et al., 2018; HONG, 2018; EKIN; ÇAĞILTAY; KARASU, 2018; MEGHDARI et al., 2018; CROVARI et al., 2019; HO et al., 2019; FISICARO et al., 2019; GARZOTTO et al., 2019; CAÑETE; LÓPEZ; PERALTA, 2021).
Motor Skills Treatment	The setup supports short-term and long-term treatments for physically impaired individuals and training fine and gross motor skills in children (e.g., *NogginStick* (SmartNoggin, 2021), *Interactive Sandbox* (Ron-Play Kids), and *Leka*) (LI; FONTIJN; MARKOPOULOS, 2008; LEE et al., 2009; GEURTS et al., 2010; DELDEN; AARTS; DIJK, 2012; GEURTS et al., 2014; VANDERMAESEN et al., 2014; GERLING et al., 2015; POSTOLACHE et al., 2017; TAM; GELSOMINI; GARZOTTO, 2017; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018; MIRONCIKA et al., 2018; FARACI et al., 2018; MERIGGI et al., 2018; HO et al., 2019; GARZOTTO et al., 2019; RIHAR et al., 2019; BORGHESE et al., 2019; YAMAMOTO et al., 2020).
Mental Healing	The setup uses bio-data and multimodal feedback to support relaxation on individuals during therapeutic or mindfulness sessions, including soothing children by intervening on contextual information (e.g., *Smart Connect* soothing system (Mattel — Fisher and Price, 2021), *Brighty Pals* (Brighty Pals, 2021), *Paro Seal* (Sense Medical, 2021)) (MUNEKATA et al., 2010; GERVAIS et al., 2016; SONNE; JENSEN, 2016; ROO et al., 2017; COTTRELL; GROW; ISBISTER, 2018; FIKAR; GÜLDENPFENNIG; GANHÖR, 2018; DESAI; MCCANN; COROS, 2018; HONG, 2018; JABBAR et al., 2019; JOHNSON et al., 2020).

Source: Author.

"stop," and "triangle" indicates movement direction).

This genre often allows customizing contents or adjusting them to the abilities or requirements of each user, and they can store play data for further analysis of performance by the educators, parents, or the users themselves (SOYSA; MAHMUD, 2019; BONILLO et al., 2019). The *Osmo* platform offers numerous SGA playsets for entertainment and home education (e.g., letters, numerals, and coding sets), including school packages for literacy lessons and STEM lessons. They offer several resources for the educators, such as mobile games, instructional videos, predefined lessons, and funding programs, which led this platform to become successfully adopted by numerous elementary school programs and teachers worldwide. Similar examples of STEM sets are *LEGO Mindstorms Ev3* (the LEGO Group, 2021), *SAMLabs* (SAM Labs, 2021), *STEM Experiment Kit* (Thames & Kosmos, 2021), *4M KidzRobotix* (Toy Smith, 2021).

Finally, the *Therapy & Rehabilitation* genre comprises ToyUI setups that assist individuals and professionals in treating several motor and cognitive skills, including addressing mental health conditions, such as distress and anxiety. For instance, the *Motor Skills Treatment* setup supports physiotherapists and occupational therapists to train patients' gross motor skills (skills involving large muscle movements) and fine motor skills – skills involving smaller muscles, such as grasping and object manipulation (POSTOLACHE et al., 2017; TAM; GELSOMINI; GARZOTTO, 2017; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018). These ToyUI setups can train individuals recovering from physical injuries or with severe physical impairments and congenital disabilities. They can also train babies and toddlers through different stages of child motor and sensory development (RIHAR et al., 2019; YAMAMOTO et al., 2020).

Similarly, the *Cognitive Skills Treatment* setup supports training skills related to essential brain development abilities (e.g., gaze coordination, visual-spatial skills, etc.) in individuals with typical or atypical cognitive development (e.g., autistic individuals and people with learning disabilities) (SOYSA; MAHMUD, 2019). For that reason, this genre offers inclusive ToyUI setups supporting social interaction among individuals with different physical and social capabilities, including intergenerational play (LEE et al., 2009; HELJAKKA; IHAMäKI, 2019). For instance, *Wheelchair Revolution* introduces an inclusive depth sensor library, *Kinect Wheels*, supporting wheelchair users playing exertion games with family members and friends (GERLING et al., 2015). Besides, these items allow modifying both the challenge and ToyUI setup configuration to meet individual needs, also incorporating editing tools and data analysis tools for professional therapists, educators, parents, or the patients themselves (HENGEVELD et al., 2009; TAM; GELSOMINI; GARZOTTO, 2017; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018).

2.2.5 Classification Data

Initially, the ToyUI classification aimed to organize ToyUI items extracted from related literature and CCI industry mappings (ALBUQUERQUE; KELNER, 2018). There is no previous classification covering both play and interface aspects in the related literature. Therefore, the feature-based classification model was also extracted from the mapped items. The systematic mapping followed the guidelines provided in the technical report *Guidelines for performing Systematic Literature Reviews in Software Engineering*, selecting 118 publications from 2008 to 2017 (KITCHENHAM; CHARTERS, 2007). Search strategies included electronic and manual search. Electronic search used the exact search string in five digital libraries (i.e., *ACM Digital Library, Springer Link, Science Direct, IEEE Xplore*, and *Scopus*). The manual search covered items from the list of references of related papers (from electronic search results), including searching on proceedings of international conferences, regular and journal special issues, and book collections. Selection criteria involved inclusion and quality criteria items seeking to assess sufficient information for data analysis. Inclusion criteria items covered items like including only primary research studies and studies published in English-language. Quality criteria items focused on assessing studies' methods and materials, detailed setup descriptions, and user evaluation studies. The industry mapping used multiple search sources (e.g., brand websites, online toy stores, crowdfunding websites, and *Google* databases). Altogether, these initial mappings gathered 153 research prototypes and 144 CCI products related to ToyUI design.

New items have kept and will most likely keep emerging in both contexts, and novel features can be incorporated while CCI technologies evolve. For instance, *MouldCraft* is a smartphone-controlled *Edutainment* console that teaches microbiology concepts using synthetic living bacteria as a toy component (KIM; POSLAD, 2019). This thesis mapped new research items released from 2018 to 2021 (search date: 23rd April 2021) to examine the ToyUI classification robustness. Systematic mapping is a time-consuming research activity, and the selection strategies adopted in the initial mapping presented a low selection rate (1.64%). The new literature mapping experimented with two new search strategies to reduce time collecting and filtering related research data. Table 10 compares the selection rate of two new search strategies in the *Google Scholar* databases using the *Publish or Perish* tool (HARZING; ALAKANGAS, 2016). The first strategy searched the keyword "smart toys" in any part of the text (including the list of references). The second search strategy required the keyword "toy" in the research title. The final selection combines results from both search strategies, resulting in 46 selected papers after removing duplicates (10 papers). The database column corresponds to the total of research papers from each search strategy. The related column shows the number of papers that introduce ToyUI setups, and selected is the number of research papers after quality criteria assessment.

Table 10 – Search strategies and literature mapping results.

STRATEGY	**DATABASE**	**RELATED**	**SELECTED**	**RATE**
Electronic Search	829	137	40	4.83%
Manual Search	6309	194	78	1.22%
2008—2017	**7138**	**331**	**118**	**1.64%**
Keyword (All Text)	955	108	41	4.29%
Keywords (Title & All Text)	107	30	15	14.02%
2018—2021*	**1009**	**122**	**46**	**4.56%**

Source: Author.

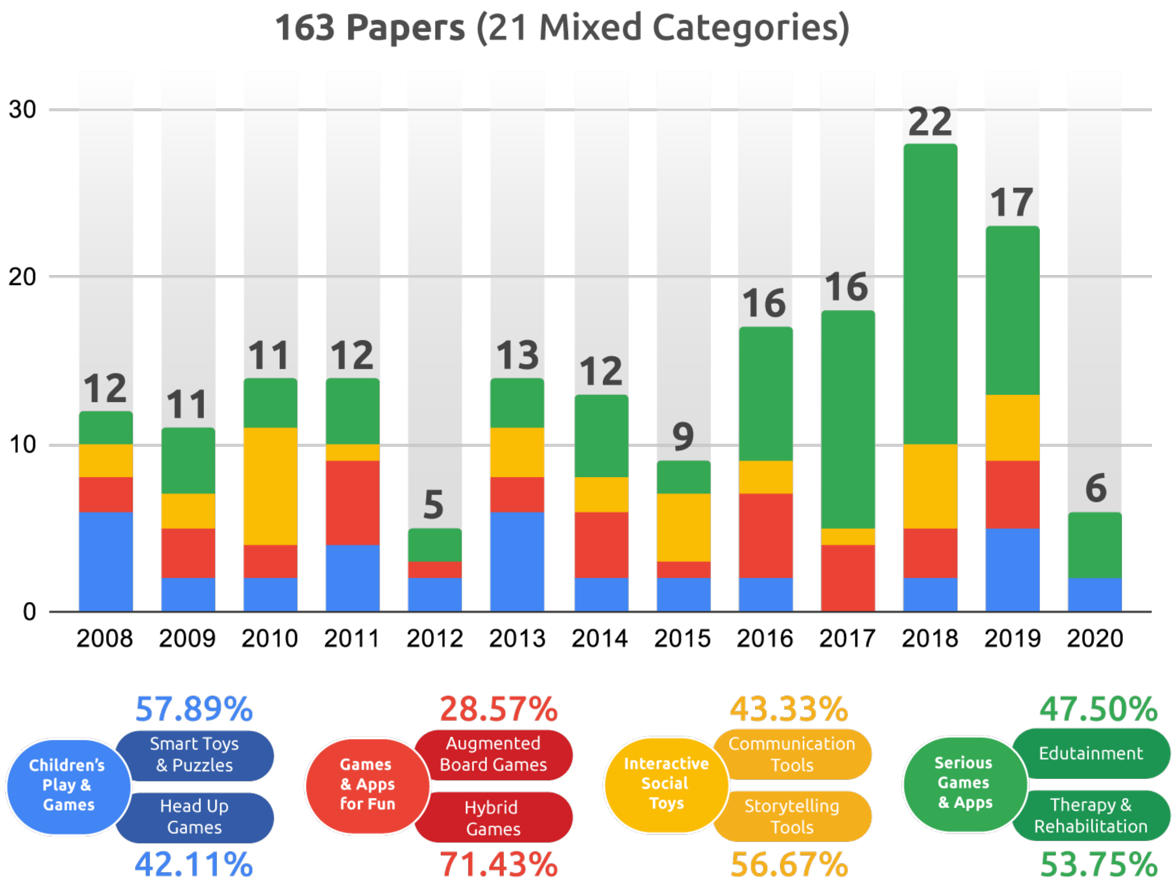
Combining the two search strategies, the overall selection rate (4.56%) is similar to previous electronic search strategy rate (4.83%). In particular, the second strategy presented a higher selection rate (14.02%), but it searched fewer items than the general keyword strategy, adding only 5 original articles to the final selection after removing the duplicates. The main reason is the inconsistent terminology adopted by the CCI research community. The term "toy" appears in 70% of research titles from the final gathering combined with terms like "smart," "sensory," "intelligent," "connected,""interactive," "robotic," IoT, and the "Internet of Toys." The term "tangible" appears in four titles, and the term "smart" often appears combined with broad terms like "environment," "learning," "space," "objects," or more specific terms (e.g., smart blocks). Another interesting finding is that the number of related items from the 3-year period is equivalent to previous 10 years of research (2008—2017) showing evidence of the increasing popularity of this CCI topic. Although 2020 selection rate was low after quality criteria, the number of 2020 related findings (33 papers) is consistent with previous years. Note that related theoretical research and research on privacy issues are not included in this gathering, and that privacy-related items and other CCI topics, such as digital and social media, and user evaluation studies also appeared in the database.

Like the initial mapping, selected research items are indexed originally by *ACM Digital Library, Springer Link, Science Direct,* and *IEEE Xplore* libraries. *Google Scholar* also indexes several other databases, and eight items were selected from other libraries after criteria evaluation (i.e., *Taylor & Francis Online, World Scientific Publishing, AIS E-Library, MPID Journals,* and *ScholarSpace*). Figure 7 shows the data scattering of mapped research items according to each category (2008—2020). A single SGA item was selected from the 2021 gathering (Jan—Apr 2021) after quality criteria assessment, and it will not be included in the data scattering (CAÑETE; LÓPEZ; PERALTA, 2021). Regarding the search for recent industry items, one conducted field research on the *117th Toy Fair New York* event between 22—25th February 2020 at the *Javits Center* (New York City, NY, United States), collecting data from 461 companies. In Figure 8, 160 companies are still active (search date: 29th April 2021) and offering novel ToyUI lines across multiple categories after combining field data with the list of companies from the previous industry mapping. An interesting finding is that many products and CCI companies from the previous mapping have discontinued toy lines or exchanged intellectual property through company acquisitions. In some cases, companies have terminated their business permanently. At the same time, novel companies appeared and will keep emerging since this industry is novel and content is constantly updating. For these reasons, one decided to present 2021 data categorizing the companies instead of products. An interactive map of active CCI companies will be available and continuously updated on this research project website[1]. A All 163 literature references appear in Tables 2—9, along with industry items representing each ToyUI setup.

According to the new data gathering, the current ToyUI classification remains robust and represents the CCI context for integrated setups. Mixed categories, genres, and setups appear in the data collection since ToyUI setups can offer parallel play features in the same setup configuration (OH et al., 2013; CROVARI et al., 2019; FISICARO et al., 2019). Some ToyUI setups can also work as platforms or "toy consoles," providing chil-

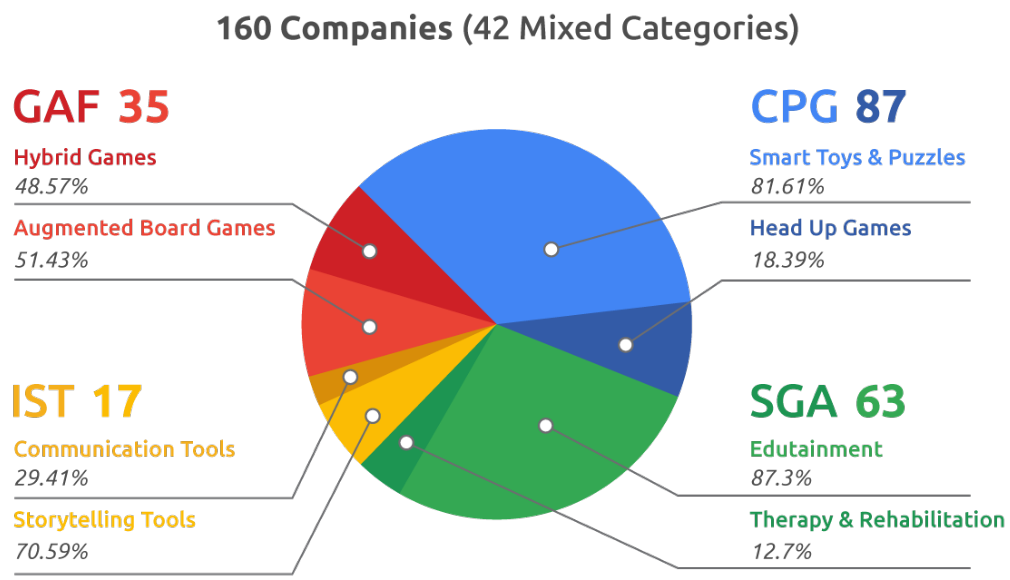
[1] www.iot4fun.com

Figure 7 – Research items distributed by year and ToyUI categories and genres.



Source: Author.

Figure 8 – CCI companies distributed by ToyUI categories and genres



Source: Author.

dren with different play activities by exchanging specific toy components in the setup configuration (e.g., *Osmo*, *Mabortic*, and *Magik Play*). Besides, several CCI companies offer ToyUI items across multiple categories in their catalogs and stores. Mixed setups appear more in the IST and SGA categories since they can incorporate interface features from other play-driven categories by focusing on the playing contents instead. For instance, *Communication Tools* intended for leisure purposes can become serious purposes tools when employed by educators, therapists, and researchers (MELONIO; RIZVI, 2016; HO et al., 2019). Therefore, instead of a restricted set of rules, the proposed ToyUI classification seeks to become a catalog of available features to guide the design of new ideas for integrated CCI design.

2.3 NON-PERSONAL DATA COLLECTION

A ToyUI setup can collect various real-time data to enable essential CCI tasks, and these types of data can fit into two groups: PD and non-PD (ALBUQUERQUE; KELNER, 2019). The PD group includes *Personal Multimedia Data, Geolocation Data*, and *Bio-Data.* First, *Personal Multimedia Data* consists of any text, image, video, or sound files that explicitly or implicitly provide information about an identifiable individual (EU, 2016; PINHEIRO, 2020). Examples are the individuals' full names in their user's accounts, face pictures or videos, and voice recording files (FARR et al., 2010; FISICARO et al., 2019). Second, *Geolocation Data* supporting pervasive play is classified as PD since GPS coordinates give means to estimate the user's location in real-time and his/her geolocation preferences, such as the user's home, work address, and recurrent locations (POURCHON et al., 2017).

Third, *Bio-Data* consists of physiological data extracted from living beings (e.g., heart rate, breath, brain waves, and electrodermal data). In ToyUI setups, bio-data serves as input to provide biofeedback, such as supporting biofeedback for physical exertion activities, including relaxation activities in *Mental Healing* setups (XU et al., 2008; ROO et al., 2017; DESAI; MCCANN; COROS, 2018; JABBAR et al., 2019). Although it is possible to retrieve bio-data anonymously, any physiological information is still considered PD (EU, 2016). For example, a system can collect bio-data and link to other user information (e.g., personal identification, medical records, and health insurance information). Data linkage can become a valuable asset for health and economic purposes, raising a series of ethical concerns (SCHWARTZ; ANDRASIK, 2017).

Regarding the non-PD group, *Non-Personal Multimedia* consists of any image, video, or audio information extracted from objects. The reasons to collect it include tracking AR-makers and image descriptors like color and texture or inserting pictures, videos, or recording sound as play content resources (VAUCELLE; ISHII, 2008; HAN et al., 2015). However, the presence of sensors like cameras and microphones can make a ToyUI setup vulnerable to collect *unauthorized PD* (i.e., collecting PD without explicitly obtaining consent or notifying the users). For example, a picture or a video intended to capture a printed AR-marker may accidentally show the user's face behind the marker. Also, embedded microphones serve to record the environment sounds like music, but they might unintentionally include the user's voice in the data collection. Therefore, a ToyUI setup may collect *unauthorized PD* when collecting non-personal multimedia data from objects due to the inherent vulnerability of setup configuration. As long as the multimedia data is essential to the system, such as inserting pictures or videos from objects to create narrative or gaming contents (e.g., *Doodlematic*) (VAUCELLE; ISHII, 2008). The ToyUI setup must always prevent collecting undesirable PD by filtering and encrypting collected information (RIVERA et al., 2019).

Only three types of non-PD are suitable for both object and user tracking: *Non-Personal Identification (NPID), Unidentifiable Positioning System (UPS),* and *Motion Tracking*. The following subsections describe them in detail and illustrate how they can support physical and social play activities in ToyUI setups. When adopting a strict non-PD collection strategy to develop ToyUI setups, creators can limit collecting PD and minimize potential harm to children's privacy in the face of implied data disclosure (ALBUQUERQUE; KELNER, 2019). Although data minimization may support mitigating risks to children's privacy, it does not exclude the need to implement other privacy by design principles and establish appropriate infrastructure for data protection (CAVOUKIAN; POPA, 2016; SHASHA et al., 2018). Implementing preventive and active measures is still necessary to protect children's privacy, such as ensuring data encryption, user authentication, and offering parental control features (RIVERA et al., 2019; ALBUQUERQUE et al., 2020; FORTES et al., 2020).

2.3.1 Non-Personal Identification

NPID identifies a real or virtual entity (object or user) without recognizing the entity as an identifiable individual. An object must represent an individual to support the NPID of users, such as using a wearable or handheld component. A ToyUI setup can define an object or user's NPID as *player one* without assigning who the *player one* is as an identifiable individual. For example, a wristband's NPID set as *player one* can identify any user wearing it as the *player one*. NPID is an essential data type for ToyUI design since it supports identifying objects and users and regulating essential play rules, such as determining behaviors and triggering play events. Table 11 describes different ways that NPID data can supply essential CCI tasks in a ToyUI setup.

Different computing technologies allow collecting NPID data from objects and users. A typical approach consists of using active identification tags like Radio Frequency Identification (RFID)/NFC tags or passive tags such as IR tags and AR-markers (e.g., fiducial markers and Quick Response (QR) codes) (WILLIS; SHIRATORI; MAHLER, 2013; MARCO; CEREZO; BALDASSARRI, 2012; BONILLO; MARCO; CEREZO, 2019). Some ToyUI setups may use computer vision techniques for feature detection and image description (e.g., the

Table 11 – Types of NPID for ToyUI

DATA TYPE	**DEFINITION**
Single NPID	A single object or user is equal to a single NPID value (e.g., a user's NPID is equal to "player one").
Multiple NPID	A single object or user represents multiple NPID values (e.g., the six faces of a cube attribute six NPID values to a single object).
Collective NPID	A combination of two or more objects (or users) creates a collective NPID value (e.g., a collection of checkers' pieces create a "player" NPID, and two or more users wearing similar belts creates a "team" NPID)).
State NPID	An object or user's NPID value updates or replaces it with a new or existing NPID value (e.g., an object's NPID "red" turns into a "blue" state after detecting another "blue" NPID).

Source: Author.

OpenCV library) to recognize an object's NPID by its shape, color, lighting, saturation, texture, or other image descriptors. However, creators must be careful when implementing ToyUI setups using AR-markers or feature detection approaches to avoid gathering any *unauthorized PD*. A resolution to this problem includes positioning the camera sensor in a specific manner to create a limited detection field, which can limit the toy component to collect the user's hand as part of multimedia data but not his/her face (AVRAHAMI; WOBBROCK; IZADI, 2011; ALBUQUERQUE; BREYER; KELNER, 2017). Active tags can become a secure strategy to collect and manage NPID data in ToyUI setups. Examples of ToyUI setups collecting NPID data through active identification, like NFC, are *Connected Toy Figurines* like *Amiibo* and the *Sifteo Cubes* platform (MERRILL; SUN; KALANITHI, 2012).

2.3.2 Unidentifiable Positioning System

A Positioning System is a mechanism that determines the location of a real or virtual entity in a designated space. UPS allows a ToyUI setup to estimate the location of objects and users without assigning them to an identifiable individual. In Table 12, UPS varies according to the motion sensor's accuracy and Degrees of Freedom (DoF). 2D positioning coordinates are often used for tabletop interaction since they determine the two-dimensional position of an object located on a plane surface. IR tabletops can recognize fiducial markers attached to the bottom of tokens, making it possible to use the same technology to gather 2D positioning and NPID data (MARCO; CEREZO; BALDASSARRI, 2012). Alternatives are ToyUI setups using conductive materials to identify tokens on the touch-screen through direct manipulation (SCHMITZ et al., 2017; FUCCIO; SIANO; MARCO, 2017; APPERT et al., 2018).

Toy components can embed sensory technology to support UPS data collection. A sensor's accuracy can range from sub-millimeters to meters and vary according to available DoF. Tracking 3D positioning coordinates, orientation, and relative positioning data are

Table 12 – Types of UPS for ToyUI

DATA TYPE	**DEFINITION**
2D positioning coordinates (X, Y)	Estimates the location of an object or user (his/her full body or body parts) in a two-dimensional plane (e.g., estimate the location of the object placed upon a table, and estimate the location of the user's body on the floor).
3D positioning coordinates (X, Y, Z)	Estimates the location of an object or user (his/her full body or body parts) in a three-dimensional space (e.g., estimate the location of a lifted object, and distinguish the location of the user's head when he/she is standing up or down).
Angular positioning (orientation)	Estimates the rotation and translation of an object or user (his/her full body or body parts) in a three-dimensional space (e.g., estimate the location of the object when it is tilted, and differentiate the location of the user's hand facing up or down).
Relative positioning (proximity)	Estimates the relative location between two or more entities in a three-dimensional space (e.g., estimate the relative location between object-to-object, object-to-user, or user's hand-to-another user's body).
Indoor Positioning System (IPS)	Estimates the 3D position of an object or user limited to an indoor space (e.g., estimate the location of the object inside a box, and evaluate the user's location inside a room).
Local Positioning System (LPS)	Estimates the 3D position of an object or user limited to a local network range. It is suitable for outdoor environments (e.g., estimate the location of the object near to a specific tree in the park, or the location of a person near to a sandpit in the backyard.

Source: Author.

standard features of commercial game controllers like the *JoyCon* (Nintendo, 2021), and *PlayStation Move* (Sony Interactive Entertainment, 2010–2016). They combine internal sensors to collect multiple DoF, such as accelerometers, gyroscopes, magnetometers, and barometers and use IR sensors to determine relative positioning from the controller to the IR emitter (usually a television or a computer display). Meanwhile, the *Leap Motion* (Ultraleap, 2021) sensor can estimate a more precise hand's positioning than a user holding a game controller, serving to manipulate both digital and physical objects in a ToyUI setup (e.g., 3D graphics or a robot's grip).

IPS and LPS support establishing a detection field ranging from centimeters to meters, and the accuracy depends on the number of accessing points, wireless beacons, and other types of emitters. An IPS using low latency tracking sensors like the *OptiTrack* (NaturalPoint, 2021) cameras can achieve a high-density detection range, allowing precise full-body motion tracking, including mapping facial expressions (BERGHMANS et al., 2016). Unlike GPS, these two UPS (IPS and LPS) permit tracking individuals by restricting access to PD collection (SHAPIRA; AMORES; BENAVIDES, 2016). In *GlowPhones*, two players interact with companion devices and distributed colorful displays placed in the environment (MERRITT et al., 2017). Together, the smartphones and distributed display antennas create an LPS Wi-Fi hotspot of 100 meters (m) range, resulting in a 25m geofence around each light. This game offers a series of game missions for the players to collaborate in launching a spacecraft by performing actions with the lights and phones, engaging players in social and physical play in the surroundings.

2.3.3 Motion Tracking

Once implemented the strategies for collecting NPID and UPS data from objects and users, it becomes possible to estimate *Motion Tracking* data. A moving physical body generates various motion tracking data, including speed and acceleration — external forces such as momentum, gravity, and atmospheric pressure also influence a moving body. Table 13 shows different ways that motion tracking data can support ToyUI design. Real-time motion tracking is a valuable resource for regulating several physical play activities and determining user performance by comparing real-time movements with the expected data collection (RIVERA et al., 2018). It appears in several genres and ToyUI setups supporting from manipulating tokens to full-body interaction.

In particular, motion tracking becomes essential to support CCI tasks in *Head-up Games*, *Playful Training*, and *Motor Skills Treatment* setups (SOUTE; MARKOPOULOS; MAGIELSE, 2010; FOGTMANN, 2011; VANDERMAESEN et al., 2014). For instance, the company *Move-2-Play* (2021) introduces a series of stuffed-ball characters (e.g., a bird, a dog, and a potato), embedding motion tracking sensors to enable tracking speed and estimating their relative positioning during play. Children can play games like *Egg Toss* and *Hot Potato* using them since the toy component can sense when the child is holding it and determine when tossed or dropped on the floor by distinguishing a soft landing from abrupt movements. Other CCI tasks include dancing games, in which embedded sensors can estimate shaking movements, including motion intensity, frequency, and relative position from the user's body parts.

2.3.4 Non-Personal Data Model

Although the many benefits of collecting PD to support contextual play, it is essential to seek alternatives for data minimization while being aware of the ethical implications of designing ToyUI setups for children (ALBUQUERQUE et al., 2020). The CCI industries can design fully functional ToyUI setups by focusing on non-PD collection strategies. The non-PD collection strategy limits data collection types to NPID, UPS, and Motion Tracking to mitigate risks to children's privacy in the event of security vulnerabilities (ALBUQUERQUE; KELNER, 2019). However, this strategy does not minimize the need to implement active and preventive data protection measures and ensure compliance with privacy protection regulations (SHASHA et al., 2018; EU, 2016; PINHEIRO, 2020).

The non-PD model, in Figure 9, can support creators in planning data management aspects. A general ToyUI setup can integrate a primary toy component with secondary

Table 13 – Types of motion tracking for ToyUI

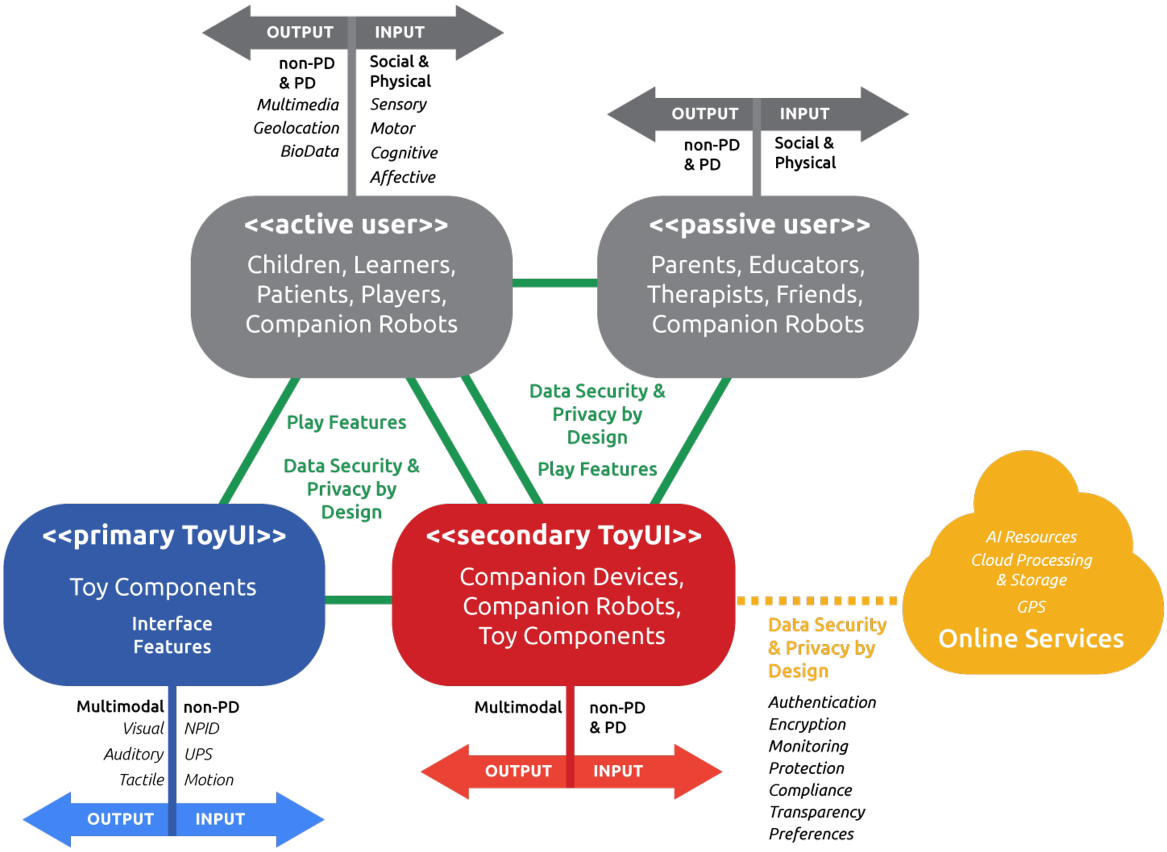
DATA TYPE	**DEFINITION**
Relative motion (trajectory)	Estimates the real-time relative positioning of the object or user (his/her full body or body's parts) from the starting location to the final one over a given time (e.g., determine if the object or the user's finger is sliding on the table, and distinguish if the user has started to walk away or run).
Circular motion (angular frequency)	Estimates the real-time radial position of the object or user (his/her full body or body parts) from the starting angular position to the final location in a given time (e.g., it determines if the object is rolling on the floor, and estimates if the user's head is rotating from left to right).
Oscillation (vibration)	Estimates the real-time 3D position of the object or user (his/her full body or body parts) by referencing a central axis and a movement frequency in a given time, (e.g., it estimates if the object is shaking, and distinguishes when a user is jumping).
Momentum (pressure)	Estimates the external forces exerted in the object or user (his/her full body or body parts) over a given period (e.g., it determines if the object has been thrown, landed or collided with another object, and distinguishes when a user is touching a soft object (when detecting atmospheric pressure).
3D Kinematics	Measures the kinematic chain movements of the object or user (its full body or body parts) in a three-dimensional space (e.g., it estimates the chain movement of a robotic arm, and tracks the user's hand gestures or dance movements).

Source: Author.

components to support multi-target audiences' physical and social play activities (ALBUQUERQUE; KELNER, 2018). In the proposed data model, the primary toy component must limit its data collection to non-PD types while offering multimodal and distributed feedback modalities to the users (i.e., visual, auditory, and tactile feedback). Regardless of local or online data processing strategies, any PD collected must occur in the secondary component, assuming it is essential and not desirable information, and ensuring the appropriate infrastructure for data protection (e.g., end-to-end encryption, access management, active monitoring, etc.) (SHASHA et al., 2018; CARVALHO; ELER, 2017; ALBUQUERQUE et al., 2020; CAVOUKIAN; POPA, 2016).

Data collection can input information from active and passive users, combining sensory, motor, cognitive, and affective aspects (e.g., memory and cultural background). Active users are the system's primary target audience, but secondary users can also present active or passive roles (e.g., parents, educators, therapists, etc.). A companion robot component can be a secondary ToyUI component or perform CCI tasks as an active or passive social actor. In Table 14, a group of nine non-PD patterns can support the pathways to planning non-PD collection for ToyUI design. Non-PD patterns comprise data sharing, data behaviors, and data storage modalities. In Figure 10, the non-PD patterns

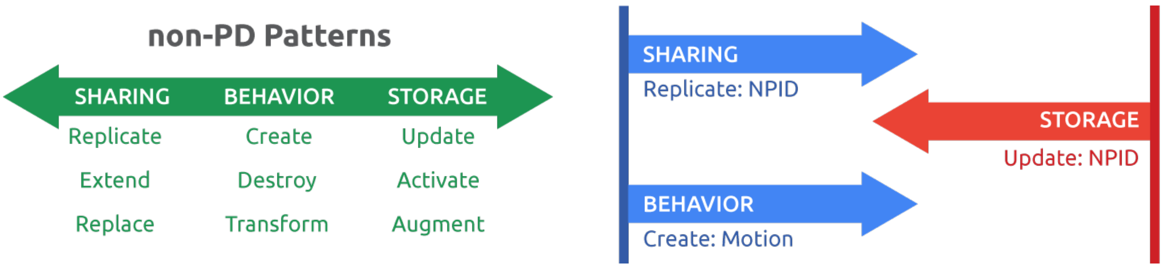
Figure 9 – An non-PD model for ToyUI design



Source: Author.

can support planning data exchanges sequences between users and ToyUI components.

Figure 10 – Examples of non-PD patterns modeling for ToyUI design.



Source: Author.

This thesis adopts the non-PD strategy to favor achieving *Privacy by Design* principles during system development. In Table 15, the authors have reviewed the initial list of principles to fit the specific context of IoT-related systems (CAVOUKIAN; POPA, 2016). In summary, when planning data collection, creators must have a precise specification of what is the purpose of data extracted for each user or system task and limit the gathering to supply the system's essential functionalities. The system functionalities must minimize PD collection beforehand, and it shall retain any data type only to fulfill the stated purposes, and then be securely erased after its usage. All implementation must follow se-

Table 14 – Examples of non-PD patterns for data collection planning.

PATTERN	**DESCRIPTION**	**EXAMPLE**
Replicate	Collective data sharing mode between two ToyUI components	The user's single NPID "zombie player" replicates another user's NPID creating a collective NPID "horde of zombies."
Extend	Multiple data sharing mode between two ToyUI components	The object's single NPID "rope" extends a virtual object's NPID "kite" creating a multiple NPID to share momentum data.
Replace	State data sharing mode between two ToyUI components	The object's single NPID "bird" replaces a virtual object's state NPID "egg" to share the object's relative motion data.
Create	Adds a new data object as the result of data collection	The real object's relative motion creates the object's single NPID "shooting" by lighting a red Light-Emitting Diode (LED) light.
Destroy	Deletes an existing data object as the result of data collection	The object's momentum data destroys the virtual object's single NPID "glass" by hitting on the projected wall.
Transform	Changes an existing data object as the result of data collection	The user's 3D kinematics transforms the virtual object's prefab "fire ball" to another prefab "water ball."
Update	Temporary data storage to record a long-lasting action	The user's state NPID "player" updates to "team red" after attaching the card's single NPID "red" to the belt.
Activate	Temporary data storage to trigger a unilateral action	The object's radial motion activates the virtual object's stated NPID "magic spell" by blinking the blue LED light.
Augment	Temporary data storage to output a specific action	The user's state NPID "full health" augments the virtual object's single NPID "health" by blinking the green LED light.

Source: Author.

curity standards for data privacy preservation that must account for data minimization, distributed data processing, encrypted data package exchanges, and securing both local and non-local data storage (SHASHA et al., 2018). Data collection, including data sharing and storage, must respect well-restricted user privacy policies (HABER, 2020). The system must offer a means for appropriate user preference settings, which must include obtaining user consent, parental control availability, and compliance with appropriate data protection regulations (FORTES et al., 2020; EU, 2016; PINHEIRO, 2020).

Table 15 – Privacy by design principles for IoT-related applications

ORIGINAL PRINCIPLES	**IoT PRINCIPLES**
Proactive not reactive; Preventative not remedial	Anticipate and eliminate opportunities for abuse
Privacy as the default setting	Configure privacy by default
Privacy embedded into design	Embed integrity into the design
Full functionality – positive-sum, not zero-sum	Fuse optimized experiences to full functionality
End-to-end security – full lifecycle protection	Clarify and simplify for protective design
Visibility and transparency – keep it open	Control monitoring and awareness
Respect for user privacy – keep it user-centric	Include users as stakeholders, not victims

Source: (CAVOUKIAN; POPA, 2016)

2.4 DISCUSSIONS

This chapter introduced the ToyUI setup definition seeking an appropriate HCI terminology for integrated CCI artifacts. The ToyUI classification organizes 22 setups into eight genres and four categories (ALBUQUERQUE; KELNER, 2018). Comprehensive literature and industry mappings (2018—2020) confirm the classification robustness in categorizing related items. Collecting user data is essential to support CCI tasks and creators can design fully functional ToyUI setups by prioritizing a non-PD collection strategy (i.e., NPID, UPS, and motion tracking). This strategy can minimize risks to children's privacy by reducing PD and preventing *unauthorized PD* collection (ALBUQUERQUE; KELNER, 2019). The Human-Centered Design (HCD) tools proposed in this thesis aim to support generating ToyUI setups across all genres and categories, adopting non-PD collection strategies to support data minimization strategies (CAVOUKIAN; POPA, 2016).

3 RELATED WORK

This chapter starts summarizing related research on Human-Centered Design (HCD) tools to support hardware–software integration in Child-Computer Interaction (CCI) and Internet of Things (IoT) related applications. The following section focuses on providing an overview of CCI industries' resources. The final section reviews data security and privacy risks for CCI and proposed some solutions (ALBUQUERQUE et al., 2020).

3.1 HUMAN-CENTERED DESIGN TOOLS

The research community has introduced different Human-Computer Interaction (HCI) tools that support hardware–software integration for Toy User Interface (ToyUI) setups and IoT related applications. Motivations to introduce HCI tools for creators include reducing authoring time and complexity when designing new ToyUI setups, defining pathways to design solutions that overcome existing issues, (e.g., hardware–software integration, mixing physical and social play, and cybersecurity issues) and empowering new audiences (e.g., co-design with teachers and children) (LEDO et al., 2018). Toolkit design supports aligning new solutions to existing User Experience (UX) design and Information Technology (IT) infrastructure and standards, enabling replication and creative exploration. Table 16 summarizes existing tools from the state-of-the-art that can support creators in different HCD stages: (A) Inspiration, (B) Ideation, and (C) Implementation. In summary, the inspiration stage includes tools supporting user research (e.g., defining the target audience and eliciting specific user requirements) and seeking existing solutions and inspirational artifacts. The ideation stage covers problem-solving tools supporting generating, selecting, and polishing concepts based on user research information and inspirational artifacts. Finally, the implementation stage covers tools supporting early prototyping of ideas to advanced functional prototypes, also evaluation tools to support collecting user feedback and performing iterative design cycles. A reminder that creators can move from inspiration to ideation and implementation in iterative cycles until final decision-making fully satisfies the stakeholders' needs. HCD tools can support training UX design and IT skills by training theoretical and technical concepts and providing practical resources, such as brainstorming resources, participatory design tools, and prototyping tools.

Inspiration tools can support creators to assemble relevant concepts for ToyUI setups, such as design affordances, interactive behavioral aspects, and technical aspects like tangible and IoT properties (BALZAN et al., 2018; GIANOTTI et al., 2020; HORNECKER, 2010; SINTORIS et al., 2018). *Ideation* tools can assist group discussion and co-design sessions and facilitate collaboration on idea generation during brainstorming sessions (GENNARI et al., 2019; HORNECKER, 2010; SINTORIS et al., 2018; ANGELINI et al., 2018). *Implemen-*

Table 16 – Overview of HCD tools from literature.

HCD	TOOL	OVERVIEW
A–B	Toy Design Framework	Conceptual framework to design toys based on pragmatic, attractive, adaptive, affective, and pesuasive affordances (BALZAN et al., 2018).
A–B	Interactive Smart Space	Conceptual framework to design interactive play installations incorporating an HCD structural model and interactive behavioral aspects (GIANOTTI et al., 2020).
A–B	TUI Cards	Card sets for brainstorming sessions based on four aspects: tangible manipulation, spatial interaction, embodied facilitation, and expressive representation (HORNECKER, 2010).
A–B	Out of the Box	Gamified card sets to train ideation skills in engineering students (SINTORIS et al., 2018).
A–B	SNaP	Cooperative board-game for co-design workshops with children to develop smart objects for outdoor environments (GENNARI et al., 2019).
B–C	IoTT Cards	Card sets to support brainstorming and prototyping sessions training tangible and IoT properties (ANGELINI et al., 2018).
B–C	Robot Storyboards	Paper-based sketch storyboards to plan Human-Robot Interaction (HRI) behaviors (MEERBEEK; SAERBECK; BARTNECK, 2009).
C	Sketch-a-TUI	Paper-based low-fidelity prototyping tool using cardboard and conductive ink (WIETHOFF et al., 2012).
C	Animated paper	Paper-based low-fidelity prototyping toolkit to design animated toys (KOIZUMI et al., 2010).
C	PaperPulse	Paper-based widgets embedding electronic circuits for prototyping interactive features without coding (RAMAKERS; TODI; LUYTEN, 2015).
C	Assembly-aware 3D	Prototyping software to design assembly-aware 3D shapes to fit hardware components and circuits (DESAI; MCCANN; COROS, 2018).
C	Origami Robots	Origami robot embodiment includes all subcomponents of a robotic system (i.e., actuation, sensing, computation, and power) (RUS; TOLLEY, 2018).

Source: Author.

tation tools, like prototypes, can present explorative, experimental, or evolutionary purposes, enabling to elicit general and specific requirements for the desired solution while supporting the extraction of valuable information for system design stages (SCHNEIDER, 1996). Low-fidelity implementation tools, such as paper prototyping, support creators to quickly sketch the ToyUI setups and assess design decisions, including HRI aspects (MEERBEEK; SAERBECK; BARTNECK, 2009; WIETHOFF et al., 2012; KOIZUMI et al., 2010; RAMAKERS; TODI; LUYTEN, 2015; RUS; TOLLEY, 2018). Paper prototypes also permit early user evaluation using the Wizard of Oz (WoZ) approach, which consists of fully or partially reproducing non-implemented behaviors of a prototype (DOW et al., 2005).

Rapid prototyping tools can make the high-fidelity implementation of ToyUI setups faster and easier for creators when selecting technologies for their designs. They offer more freedom to edit and test design features in different implementation stages (SOUTE et al., 2017). This thesis classifies related rapid prototyping tools into smart devices, Augmented Reality (AR)-based platforms, mobile-based platforms, and hardware toolkits (ALBUQUERQUE et al., 2020). In Table 17, each type of rapid prototyping tool has its pros and cons. Smart devices can be the toy components themselves (SOUTE et al., 2017; SEGURA et al., 2013; MERRILL; SUN; KALANITHI, 2012). They are ready to use and play and usually promote inter-device connection and embodied interaction. Although they present a fixed shape that may limit editing features, creators can enclose the smart device into a physical enclosure (a toy component) to prototype new interface features (LEDO et al., 2018).

AR-based platforms use cameras to detect objects (e.g., tokens, cards, and toys) by using either marker-based and markerless recognition techniques (i.e., recognition of shape, color, lighting, saturation, texture, and other image descriptors) (GOHLKE; HLATKY; JONG, 2015; MARCO; CEREZO; BALDASSARRI, 2012; WU; HOUBEN; MARQUARDT, 2017). The AR-based approach often requires a complex setup to support player and object detection and to display virtual contents, such as monitors, Head-Mounted Displays (HMD), projectors, Infrared (IR) tabletops, and kinetic sensors (BONILLO; MARCO; CEREZO, 2019). Note that AR-based platforms may expose the user's privacy due to the collection of Personal Data (PD), such as facial pictures or videos of the players manipulating the toy components. Mobile-based platforms explore multitouch, conductive materials, or contactless technology like Radio Frequency Identification (RFID)/Near-Field Communication (NFC) to detect objects also connecting with mobile devices (e.g., smartphones and tablets). This approach reduces setup complexity and privacy issues when compared with the AR-based platforms. However, many platforms are also limited to promote token-tabletop interaction – such as placing and moving tokens on the touchscreen (FUCCIO; SIANO; MARCO, 2017; BECH et al., 2016; APPERT et al., 2018). Research on flexible materials has permitted more design freedom when implementing interface features (SCHMITZ et al., 2017; JIN et al., 2018).

Hardware toolkits consist of sensors, actuators, communicators, and other electronic circuits attached and programmable (KAZEMITABAAR et al., 2017; RATHFELDER; HIPP, 2019; BERZOWSKA et al., 2019; WOOD et al., 2019). They offer more freedom to edit both play and interface features since they permit creators to select components that best fit their projects. However, the level of editing freedom, size, and distribution of the hardware components influences the rapid prototyping tool adaptability (ALBUQUERQUE et al., 2020). Software technology to design assembly-aware 3D models for digital fabrication can support overcoming these issues by adapting the toy component constraints (DESAI; MCCANN; COROS, 2018). Incorporating modularity aspects in a hardware toolkit can improve its adaptability (WANG et al., 2016; WHELER et al., 2020). Hardware toolkits may also bring challenges to support local and online data protection when offering wireless connectivity features (KNOWLES et al., 2019).

Robot embodiment features define the constraints in which creators can develop HRI

Table 17 – Overview of rapid implementation tools from related literature.

TYPE	**TOOL OVERVIEW**
Smart Device	**RaPIDO**. Colorful smart devices connected via RF to prototype head up games (SOUTE et al., 2017).
Smart Device	**Body Bug**. Spheric smart device enabled for motion tracking to prototype full body interaction games (SEGURA et al., 2013).
Smart Device	**Sifteo Cubes**. Cubic smart devices with a touchscreen display connected via NFC (MERRILL; SUN; KALANITHI, 2012).
AR-based Platform	**Sketching LEGO**. A tabletop that enables color detection of LEGO bricks to prototype passive widgets (GOHLKE; HLATKY; JONG, 2015).
AR-based Platform	**NIK Vision**. IR tabletop that enables fiducial markers detection to prototype passive widgets (MARCO; CEREZO; BALDASSARRI, 2012).
AR-based Platform	**EagleSense**. A top-view tracking system combining depth and IR cameras for tracking user posture and activities (WU; HOUBEN; MARQUARDT, 2017).
AR-based Platform	**JUGUEMOS**. A toolkit to support object, table, and room augmentation by integrating heterogeneous devices using OSC protocol (BONILLO; MARCO; CEREZO, 2019).
Mobile-based Platform	**TriPOD**. Passive widgets toolkit for touchcreens using capacitive pins and copper (FUCCIO; SIANO; MARCO, 2017).
Mobile-based Platform	**Widgets**. Passive widgets toolkit for touchcreens using aluminium foil and conductive tape (BECH et al., 2016).
Mobile-based Platform	**Flexibles**. Active widgets toolkit using conductive 3D-printed materials for digital applications (SCHMITZ et al., 2017).
Mobile-based Platform	**TouchToken**. Passive widgets toolkit for touchscreens and IR tabletops (APPERT et al., 2018).
Mobile-based Platform	**WiSh**. Flexible mesh layer of RFID tags supporting shape-aware surface detection and wireless connectivity (JIN et al., 2018).
Hardware Toolkit	**CircuitStack**. Modular and stackable printed circuit boards to support prototyping of IoT-related projects (WANG et al., 2016).
Hardware Toolkit	**MakeWear**. Wearable coding kit made of 32 modules among sensors, receivers, actuators, and logic blocks (KAZEMITABAAR et al., 2017).
Hardware Toolkit	**DermaPad**. Prototyping board to support bio-data collection (e.g., skin conductance and pulse oximetry) and biofeedback, also embedding accelerometer and a touch sensor (RATHFELDER; HIPP, 2019).
Hardware Tookit	**Baby Tango**. Electronic textile toolkit for designing soft toy components supporting full-body interaction (BERZOWSKA et al., 2019).
Hardware Toolkit	**BBC micro:bit**. Prototyping board for children, supporting Micro USB, crocodile clips, or banana plugs. It embeds a LED matrix, magnetometer, and accelerometer sensors and offers wireless, Bluetooth, and RFID connectivity. (AUSTIN et al., 2020).

Source: Author.

tasks in a ToyUI setup. Social robot models are still high-cost resources, and not many institutions or companies have them available to test and use daily. Robot software development has not yet reached a broader audience, and robot applications can remain restricted to business showcases, research facilities, and educational or health institutions. Resources are more limited in developing countries, and Do-It-Yourself (DIY) robots can become a solution to support robot design, research, and education (PANDIAN, 2018; BJÖRLING; ROSE, 2019). Researchers have proposed low-cost and custom robot embodiment manufacturing using essential hardware components and inexpensive materials, such as *Puffy*, the inflatable therapeutic robot (GARZOTTO; GELSOMINI; KINOE, 2017). In another example, *Pop-bots* is a low-cost robot Artificial Intelligence (AI) platform for children using smartphones and building blocks. It supports robot embodiment features and implementing an AI-based curriculum for Science, Technology, Engineering, and Mathematics (STEM) programs (WILLIAMS; PARK; BREAZEAL, 2019).

3.2 CHILD-COMPUTER INTERACTION INDUSTRIES

There is limited information on how CCI industries use HCD and other design tools to support the development of hardware–software integrated systems, such as ToyUI setups. In several circumstances, the design process and results are, to some extent, experimental, and CCI industries are still learning how to develop integrated CCI experiences while seeking suitable design practices (TYNI; KULTIMA, 2016). Traditionally, the process of creating new play systems in this sector is primarily marketing-oriented. Design methods and tools include performing focus-group sessions, customer surveys, participatory sessions, applying gender typification strategies, and licensing transmedia contents from beloved franchises like *Star Wars, Harry Potter,* and *Marvel* (LAUWAERT, 2009; EISEN; MATTHEWS; JIROUT, 2021). In that sense, marketing-oriented strategies may also guide creators from inspiration to ideation and implementation of the ToyUI setups in the CCI industries.

According to market reports published by the United Kingdom-based group *Juniper Research* (July 2017 and May 2018), a particular strategy is to separately price hardware and software components. *Juniper Research* estimates that the purchase of in-app content will reach 25% of this sector's total revenue (17.7 billion USD) by 2023. Many ToyUI setups offer to purchase independent physical components (e.g., collectibles and toy sets) and digital components (e.g., seasonal items and narrative content) in the companion applications (DHAR; WU, 2015). However, the independent pricing strategy may also reflect the design of ToyUI setups and the CCI experience promoted by them. For instance, in the former *Furby Connect* (Hasbro, 2016—2019) setup, the toy component and companion application are entirely independent components that can promote CCI while disconnected. In another example, the CCI experience from using *Amiibo* (Nintendo, 2021) collectible figures limits to add new content and unlock special features in the digital game, while the actual playing time focuses on traditional joystick—screen interaction.

The CCI industries can benefit from rapid implementation tools that facilitate hardware–software integration of ToyUI setups. In Table 18, some industry technologies are comparable to rapid prototyping tools from the literature. Smart devices examples include game controllers and handheld robots like *Sphero* and *Ozobot* robots. Mobile and AR-based technology have demonstrated effective adaptation to different solutions, but they often focus on manipulating tokens. For instance, the *Osmo* platform offers various manipulatives to interact with mobile applications (e.g., letters, numerals, shapes, block coding, etc.). In another example, *TapTop* is a platform for *Augmented board games* that supports recognizing conductive figurines in a large touchscreen display. The French company *Volumique* develops technologies and licenses for the CCI industries. Their conductive touchpoints license portfolio includes clients like *Hasbro* and *Oniri Islands* (Tourmaline Studio, 2021). Another *Volumique* technology appears in the board-game *World of Yo-ho*, which uses motion information to predict the smartphone 2D-positioning on a physical game board.

Table 18 – Overview of industry rapid prototyping tools.

TYPE	**TOOL OVERVIEW**
Smart Device	**Labo.** Card-board bodies enclose the *JoyCon* controller functions (motion tracking, depth sensor, vibration, NFC, and Bluetooth connection) (Nintendo, 2021).
Smart Device	**SPRK+**. Spherical robot embeds several motors, and motion, proximity, and lighting sensors (offers Bluetooth connection) (Sphero, 2021)
Smart Device	**EVO.** Semi-spherical robot embeds motors, and proximity and optical sensors (offers NFC and Bluetooth connection) (Ozobot, 2021)
AR-based platform	**Osmo.** The mirrored device attaches to the tablet's front-camera to allow object detection using a mobile application (Tangible Play, 2021)
AR-based platform	**Plugo.** Detection field station for playing mobile games using the tablet's front-camera, manipulatives, and other toy sets (Play Shifu, 2021).
Mobile-based platform	**Volumique.** 3-coordinates recognition patent to build self-capacitive manipulatives for touchscreen applications (Volumique, 2021)
Mobile-based platform	**TapTop.** Large tabletop platform supporting self-capacitive manipulatives for augmented board games (Blok Party, 2021)
Mobile-based platform	**Tori.** Contactless identification board supports identifying objects and mid-air interaction with mobile applications (Bandai Namco, 2021)
Hardware Toolkit	**SAM labs.** Modular cubic components (sensors, actuators, motors, connectors, etc.) that are programmable by an application via Bluetooth (SAM Labs, 2021).
Hardware Toolkit	**Crazy Circuits – Bit Board.** Modular circuit boards (sensors, actuators, motors, etc.) are attached to LEGO blocks and compatible with other prototyping boards like *Arduino* and *BBC micro:bit* (Brown Dog Gadgets, 2021).

Source: Author.

Programming Toy-kits can offer more editing freedom, but available coding functions focus on children's coding skills and DIY projects. *SAM Labs* and *LittleBits* hardware toy kits use mobile applications for coding. Although they support kids on various "maker" and DIY projects, a more robust technical specification is required to support professional prototyping. Hardware toy kits like *Crazy Circuits* can integrate with prototyping boards like *Arduino* (Arduino, 2021) and the *BBC micro:bit* (AUSTIN et al., 2020). When it comes to facilitating hardware–software integration, compatibility with existing software development tools play a crucial role in supporting the CCI community. Software development for ToyUI setups can include everything from web-based application environment, mobile software development (e.g., *Android Studio* (Google, 2021) and *iOS Xcode* (Apple, 2021)), game engines (e.g., *Unity 3D* (Unity Technologies, 2021) and *Unreal Engine* (Epic Games, 2021)), and Robot Operating System (ROS), such as *Gazebo* (Apache, 2021), and other proprietary robot simulators and Software Development Kit (SDK). It becomes essential that rapid implementation tools provide a robust (and preferred) open-source Integrated Development Environment (IDE) with available web, mobile, game, ROS, and SDKs.

3.3 DATA SECURITY AND PRIVACY SOLUTIONS

Finally, there are significant studies addressing privacy and data security issues related to ToyUI setups. A systematic literature review selecting 26 primary studies (published between 2009—2019) provides a complete and recent overview of children's privacy risks in ToyUI setups (ALBUQUERQUE et al., 2020). In summary, most studies (20 of 26) focus on data breach-related risks and propose technical recommendations for stakeholders (CHOWDHURY, 2018; ESPINOSA-ARANDA et al., 2018; KSHETRI; VOAS, 2018; CARVALHO; ELER, 2018b; CARVALHO; ELER, 2018a; MAHMOUD et al., 2017; MOINI, 2016; CARVALHO; ELER, 2017; PLEBAN; BAND; CREUTZBURG, 2014). The following studies also address risks related to children's physical safety (CHU; APTHORPE; FEAMSTER, 2019; YANKSON et al., 2019b; SHASHA et al., 2018; FANTINATO et al., 2018; DEMETZOU; BÖCK; HANTEER, 2018; RAFFERTY et al., 2017; HUNG; FANTINATO; RAFFERTY, 2016; HUNG et al., 2016; YONG et al., 2011), psychological safety (SHASHA et al., 2018; HAYNES et al., 2017; VALENTE; CARDENAS, 2017; JONES; MEURER, 2016b; DENNING et al., 2009), unauthorized remote control (HOLLOWAY; GREEN, 2016; PLEBAN; BAND; CREUTZBURG, 2014; DENNING et al., 2009), dataveillance (SMITH; SHADE, 2018; HOLLOWAY; GREEN, 2016), and other ethical aspects (DEMETZOU; BÖCK; HANTEER, 2018; MCREYNOLDS et al., 2017; JONES, 2016).

According to this gathering, most existing vulnerabilities in ToyUI setups are easily correctable with existing IoT resources and likely related to the creator's decisions on cybersecurity practices (CHU; APTHORPE; FEAMSTER, 2019). Sixteen studies propose technical recommendations for creators, and four studies make additions to pertinent laws and privacy protection regulations (CHOWDHURY, 2018; MCREYNOLDS et al., 2017; MOINI, 2016; HUNG; FANTINATO; RAFFERTY, 2016; HOLLOWAY; GREEN, 2016). Besides, eight studies contribute to parental control mechanisms (FANTINATO et al., 2018; CARVALHO; ELER, 2018b; CARVALHO; ELER, 2018a; CARVALHO; ELER, 2017; MCREYNOLDS et al., 2017; RAFFERTY et al., 2017; HUNG; FANTINATO; RAFFERTY, 2016; HUNG et al., 2016). Technical recommendations for creators vary from listing lessons learned to best practices and system requirements, also proposing evaluation frameworks (SHASHA et al., 2018; HAYNES et al., 2017; MAHMOUD et al., 2017). This study strongly suggests that creators must address these vulnerabilities in the early stages of system development (AL-BUQUERQUE et al., 2020). HCD tools supporting decision-making can potentially assist them in overcoming most vulnerabilities. However, a critical challenge remains on to delivering practical tools that the CCI industries can easily absorb. A combined effort from the research community, public and private institutions, including parents and society as a whole is necessary to facilitate toy makers adopting best cybersecurity practices and enforcing compliance with privacy protection standards and regulations.

3.4 DISCUSSIONS

The CCI research community and industries can benefit from HCD tools to improve system development strategies when designing ToyUI setups. HCD tools can intervene from the early stages of system development, from inspiration to brainstorming, co-design, and participatory design sessions, including different implementation stages and prototyping fidelity levels. The CCI industries can benefit from solutions that support creators in overcoming UX design (e.g., problem-solving and decision-making) and IT aspects (e.g., data privacy preservation and compliance with data protection regulations). Instead of focusing on a single tool or intervention, a combined effort intervening in all HCD stages must account for users and technology diversity, adaptability features, and the various interface paradigms that ToyUI design can promote. The related literature still misses a HCD toolkit integrating different tools across these three stages, and this research thesis fulfills this research gap. The proposed HCD tools support a systematic, integrated, and iterative problem-solving process using individual and collaborative tools to support interdisciplinary teams in decision-making during system development. This thesis introduces seven original tools (i.e., ToyUI classification, brainstorming ToyUI, data collection planning, storyboard robot ideas, stickers ToyUI, MiMi AI Robot, and IoT4Fun toolkit) and adapts supporting tools from the literature (i.e., ToyUI Design Document, System Usability Scale (SUS), and SUS-Kids) (RYAN, 1999; BANGOR; KORTUM; MILLER, 2008; PUTNAM et al., 2020). Novel HCD tools can become part of the ToyUI toolkit as it evolves in future works.

4 RESEARCH METHOD

This chapter presents the thesis research method using the *Design Science Methodology (DSM)* framework. DSM concerns the design and investigation of artifacts in context (WIERINGA, 2014). Specifically, DSM refers to artifacts that interact with a problem context to improve something in that context. This chapter comprises four sections: *Problem Investigation, Treatment Design, Treatment Validation,* and *Treatment Evaluation.*

4.1 PROBLEM INVESTIGATION

First, the *Problem Investigation* aims to gather information about the stakeholders' needs and goals (WIERINGA, 2014). The primary stakeholders of this thesis are the Toy User Interface (ToyUI) creators, which come from interdisciplinary backgrounds. ToyUI creators are designers, engineers, developers, and other Information Technology (IT), marketing, and business professionals (TYNI; KULTIMA, 2016; DHAR; WU, 2015). Other stakeholders such as educators, therapists, and the children themselves can be included as creators in system development through co-design and participatory design strategies (YAROSH; SCHUELLER, 2017; BJÖRLING; ROSE, 2019). In the Child-Computer Interaction (CCI) industries, interdisciplinary teams also include partnerships with inventors and outsourcing companies (NI; FLYNN; JACOBS, 2016). For instance, two United States (US)-based companies *Learning Resources* and *Educational Insights* adopt partnerships with inventors as part of their business model, and examples are the *Coding Critters* (Learning Resources, 2021) and the *Circuit Explorer* (Educational Insights, 2021). Examples of outsourcing companies supplying the CCI industries are software and Mixed-Reality (MR) technology companies like *Wow! Stuff, HitPoint, Killer Snails,* and *Chicken Waffle.* Table 19 summarizes the stakeholders and their goals.

IT outsourcing is a common practice in the CCI industries. It can enable breaking technical and entry barriers for companies that wish to introduce technology in system design without previously working with software design or electronics in general. However, outsourcing can become an issue in aligning design goals during iterative system development, including raising safety issues for customers and investors (NI; FLYNN; JACOBS, 2016). During field research at the *Toy Fair New York (NY) 2020* event, CCI industries representatives described their experience with IT outsourcing. Creators can send design materials to IT companies, including interface mock-ups to fully user interface design assets before any technical implementation. Other challenges related to IT outsourcing include maintaining the product life cycle active (e.g., software updates and technical support) and overcoming issues related to data-breach vulnerabilities and compliance with privacy policies (ALBUQUERQUE et al., 2020). There are several cases of IT

Table 19 – Overview of stakeholders' goals

STAKEHOLDER	GOALS
ToyUI creators (e.g., designers, engineers, developers, etc.)	Develop innovative ToyUI setups that support physical and social play activities and meet privacy by design principles.
IT outsourcing companies	Support ToyUI teams from CCI industries supplying them with hardware–software integrated solutions.
Primary users (e.g., children, neurodivergent individuals, etc.)	Actively experience play or content-driven activities promoted by the ToyUI setups.
Secondary users (e.g., parents, educators, therapists)	Passively experience play or content-driven activities promoted by the ToyUI setups, including monitoring activities with primary users.
CCI industries stakeholders (e.g., business, manufacturers, suppliers)	Distribute and sell innovative ToyUI setups that support physical and social play activities seeking economic interests (e.g., profit, increase sales, branding, etc.).
Educational and Healthcare Institutions	Employ ToyUI setups to promote play or content-driven activities for primary and secondary users (i.e., clients).
Regulatory Institutions	Inspect ToyUI setups features according to international and local industry standards (e.g., safety, compliance with data protection regulation, etc.).

Source: Author.

startups supporting traditional toy brands and companies with essential system services (e.g., voice processing services, cloud storage, and online processing services). IT outsourcing can introduce vulnerabilities regarding data protection practices they adopt, including temporary or permanent termination of services provided by outsourcing companies.

An illustrative scenario for IT outsourcing issues happened between *Mattel*, the startup *PullString* (former *ToyTalk*), and *Apple*. In *Toy Fair NY 2015*, *Mattel* first announced their partnership with *ToyTalk* to release the *Hello Barbie* Wi-Fi doll. As discussed in this thesis, the *Hello Barbie* appears in several CCI and Internet of Things (IoT) studies on dataveillance, physical and psychological safety, data-breach, and privacy policies compliance (MANTA; OLSON, 2015; JONES; MEURER, 2016a; MOINI, 2016; TAYLOR; MICHAEL, 2016; MERTALA, 2020; HABER, 2020). Privacy issues may influence customers' perceptions and purchase intent (FANTINATO et al., 2018). However, circumstances that led *Hello Barbie* to discontinuity were mainly motivated by *PullString's* decision to interrupt voice processing services after the startup acquisition by *Apple* in 2019. Despite all hurdles related to ToyUI design, investing in technology still is part of *Mattel's* strategic plan to increase toy sales and social media presence (GILLIARD; HOFFMAN; BAALBAKI, 2019).

The ToyUI creators' primary goal is to design ToyUI setups that promote integrated CCI experiences while being aware of ethical aspects related to children's privacy rights –

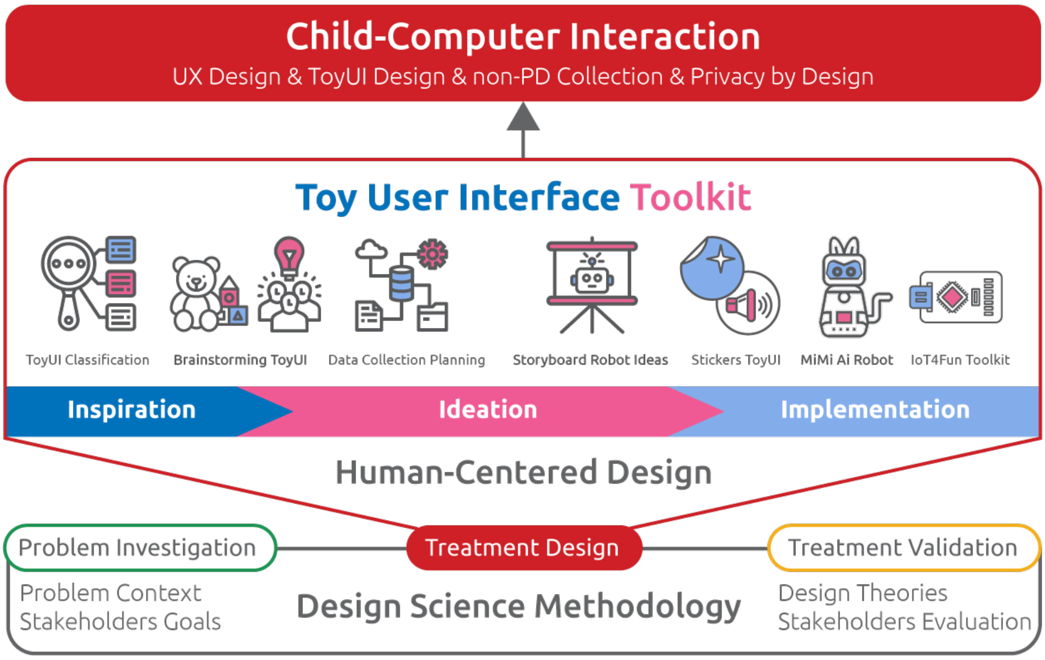
bringing us to the secondary stakeholders of this research: the users. The users are children of different age groups, including their parents, family members, and other individuals, such as educators, therapists, caregivers, etc. Sometimes individuals may have various physical, sensory, and cognitive disabilities and impairments, which demand specific design needs and solutions (REGAL et al., 2020; BORGHESE et al., 2019; FISICARO et al., 2019). Altogether, ToyUI users main goal is to experience CCI motivated by various purposes (e.g., leisure and serious purposes) (ALBUQUERQUE; KELNER, 2018). On the other side, the CCI industries target users as potential customers. Customers in CCI industries also include educational and healthcare institutions (e.g., schools, hospitals, clinics, etc.). In this context, institutions are secondary users who target primary users (individuals) as their clients (e.g., students and patients).

Other stakeholders from the CCI industries cover business stakeholders such as manufacturers, suppliers, investors, and retailers (e.g., *The Foland Group* and *Super Ventures*). Marketing stakeholders include franchises, brands, and sales representatives (e.g., *Prodigy Works*). The primary goals of CCI industries' stakeholders are to make sales and generate revenue in the Industry. Essential stakeholders to this problem context also include post-secondary educational institutions since they provide human resources to the CCI industries (e.g., Industrial Design, Computer Science, Mechanical and Electronic Engineering, IT and Business programs, among others). Also, regulatory standards institutions like private, governmental, and not-for-profit institutions provide testing, inspection, and certification services. Examples are *TUV Rheinland* and the *Intertek Group* – the last offers cybersecurity inspection services for IoT-related applications. Other relevant institutions are Industry associations like the *Women in Toys* association and the *Toy Association*, which organizes the annual *Toy Fair* events and the *Toy of the Year (TOTY)* awards.

4.2 TREATMENT DESIGN

The *Treatment Design* consists of selecting existing artifacts or proposing new ones to fulfill stakeholders' needs and goals (WIERINGA, 2014). This thesis introduces a Human-Centered Design (HCD) toolkit to support creators during the design and development of ToyUI setups. The ToyUI Toolkit aims to support User Experience (UX) design skills like problem-solving and decision-making, and IT skills on data collection planning and management. The specific goals are assisting creators with hardware–software integration aspects and implementing ToyUI setups that prioritize the non-Personal Data (PD) collection strategy (ALBUQUERQUE; KELNER, 2019). The premise is that facilitating hardware and software integration can benefit the UX during CCI while allowing the non-PD collection strategy can favor meeting privacy by design principles and regulatory standards for children's privacy protection (ALBUQUERQUE et al., 2020; CAVOUKIAN; POPA, 2016). Figure 11 details the treatment design according to the DSM framework. Table 20 introduces each HCD tool and how they fulfill the primary stakeholders' goals during system development.

Figure 11 – Proposed treatment design to address the ToyUI problem context.



Source: Author.

Table 20 – Overview of the treatment design according to stakeholders' goals

HCD TOOL	STAKEHOLDER'S GOALS
ToyUI Classification	Conduct feature-based analysis of ToyUI setups to support context investigation and user research.
Brainstorming ToyUI	Generate ideas based on toys and game features, and creative constraints.
Data Collection Planning	Classify ideas based on potential privacy and security issues and overcome vulnerabilities by adopting a non-PD strategy.
Robot Storyboard Ideas	Detail Human-Robot Interaction (HRI) ideas including robot embodiment and user research information.
Stickers ToyUI	Use paper-based embodiment, sensors, and actuators to support low-fidelity prototyping.
MiMi AI-Robot	Implement and test Artificial Intelligence (AI) features using open-source resources and a low-cost robot embodiment.
IoT4Fun Toolkit	Use a rapid prototyping toolkit based on non-PD approach to support hardware and software integration.

Source: Author.

In early 2020, the entire world was surprised by the effects of the COVID-19 pandemic. Every group in the society was, to some extent, affected by the pandemic and the necessary social distancing measures (NICOLA et al., 2020). Many industries had to either suspend or transfer suitable activities to remote settings (KAHN; LANGE; WICZER, 2020). From children to college and university, students were suddenly forced to interrupt regular learning activities. Educational institutions had to quickly adapt the learning activities to hybrid, remote, or online alternatives (VINER et al., 2020; GONZALEZ et al., 2020). For instance, all stakeholders' evaluation sessions have occurred remotely since 2020. For that reason, the treatment design also accounts for this emergent context by implementing versions of the ToyUI Toolkit supporting remote learning and teamwork. This thesis proposes alternatives to all HCD tools. However, only the following tools were fully implemented and evaluated by stakeholders: *ToyUI Classification, Brainstorming ToyUI, Data Collection Planning, Robot Storyboard Ideas,* and *Stickers ToyUI.*

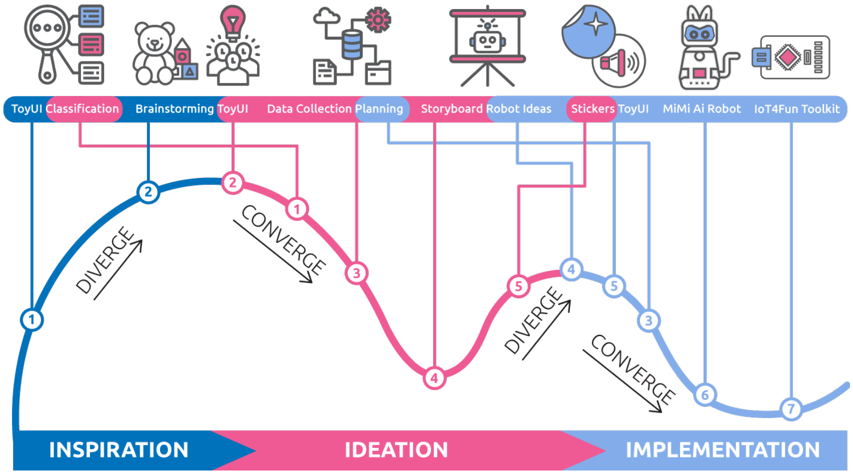
4.3 TREATMENT VALIDATION

The *Treatment Validation* concerns how artifacts behave within the problem context by analyzing them against pertinent design theories (WIERINGA, 2014). First, according to ISO 9241-210:2019, hardware–software integrated systems designed by HCD principles offer a set of qualities, including increased productivity and operational efficiency (GROUP et al., 2010). HCD principles support developing systems that are easier to understand and use, reducing training and support costs, and enhancing usability to a broader audience. HCD also promotes accessibility, improves UX, reduces discomfort and distress, provides competitive advantages, and contributes to sustainability objectives. Second,this thesis proposes incorporating the non-PD strategy in data collection planning to favor achieving *Privacy by Design* principles during system development, as discussed in the theoretical background (refer to **Chapter 2**). The goal is to support stakeholders seeking more design opportunities while being aware of the potential ethical and privacy-related issues for designing integrated artifacts for children, such as data minimization and eliminating opportunities for abuse (CAVOUKIAN; POPA, 2016).

In Figure 12, treatment validation distributes the ToyUI Toolkit into three stages, namely inspiration, ideation, and implementation. The current ToyUI Toolkit consists of seven design tools, each one distributed into two HCD stages. The first tool diverges the problem-solving process seeking inspirational artifacts to generate a high volume of ideas based on initial user research information between inspiration and ideation. Then, idea selection converges the problem-solving process applying data collection strategies to support idea selection and decision-making. Next, from the ideation to implementation, the selected ideas diverge into problem-solving alternatives through planning and prototyping. Then, the prototypes converge into decision-making when functional implementation sets the interface and play features. Finally, user evaluation sessions permit the HCD cycle to diverge again, seeking inspiration from user feedback. Then, another ideation round converges into new features to implement iterations in the existing prototype. Creators keep performing problem-solving tasks from inspiration to ideation and implementation in iterative cycles until final decision-making fully satisfies the stakeholders' needs.

In summary, the ToyUI toolkit covers the following HCD principles to achieve the

Figure 12 – Treatment validation according to HCD principles.



Source: Author.

stakeholders' goals stated in Table 20. First, the design relies on a clear understanding of the context of use, which covers the user's needs, the interaction environment, and other stakeholders. Users participate in the design and development steps, which must be iterative and driven by user-centered evaluations. The design process accounts for the whole UX, and an interdisciplinary team with complementary skills and perspectives conveys it. The ToyUI Toolkit introduces the data collection planning and rapid prototyping tools fully supporting the non-PD collection strategy in the ideation and implementation stages to favor achieving privacy by design principles.

4.4 TREATMENT EVALUATION

Finally, the *Treatment Evaluation* stage consists of evaluating the *treatment design* with stakeholders in a real-world scenario (WIERINGA, 2014). According to a literature review on toolkit evaluation strategies, Human-Computer Interaction (HCI) toolkits evaluation can use four strategies: demonstration, usage, performance, and heuristics (LEDO et al., 2018). Demonstration evaluation strategies include designing novel and replicated examples, individual case studies, and demonstrating different design spaces. Usage-oriented evaluations include usability studies, A/B comparison, walk-through, observation, and take-home studies, including eliciting user feedback through Likert scales questionnaires or interviews. Performance evaluations include benchmark threshold and comparison, and heuristics evaluation includes checklists, discussions, and basing usage studies on existing heuristics. This thesis selected demonstration and usage strategies to evaluate the ToyUI Toolkit since performance and heuristics evaluation strategies depend on previous benchmarks and a list of existing items, respectively. This research field still lacks defining benchmarks to support threshold comparison and a list of heuristics to evaluate the designs.

Demonstration evaluation uses proof-of-concept designs to clarify how the ToyUI Toolkit's capabilities enable the claimed applications and design principles. Usage evaluation involves external users working with the ToyUI toolkit (LEDO et al., 2018). Both evaluations must include the three HCD stages (i.e., inspiration, ideation, and implementation) and follow the goals stated in this research to support achieving privacy by design principles (e.g., adopting the non-PD collection strategy and other data minimization strategies). The expected outcome is that prototypes developed using the ToyUI Toolkit are expected to incorporate HCD and privacy by design principles. The ToyUI prototypes can be high-fidelity prototypes, low-fidelity prototypes, and digital prototypes. High-fidelity prototypes are partially or fully functional prototypes, implementing both hardware and software components (e.g., toy components embedding electronics, computer vision systems, and robot applications). In contrast, low-fidelity prototypes are non-functional prototypes, such as paper prototypes and software mockups. Digital prototypes are partially or fully functional prototypes that implement software components.

Demonstration evaluations consist of functional prototypes designed through the guidelines and tools provided by the ToyUI Toolkit. Usage evaluation consists of long-term and short-term sessions with primary stakeholders partially or fully using the ToyUI Toolkit. The ToyUI Toolkit primary stakeholders are interdisciplinary professionals from the CCI industries – the creators. As detailed in the problem investigation, the ToyUI creators are designers, engineers, developers, and other IT, marketing, and business professionals (TYNI; KULTIMA, 2016; DHAR; WU, 2015). Therefore, the treatment evaluation includes stakeholders from these mentioned fields, among researchers, graduate students, undergraduate students, and professionals. Long-term usage evaluations of the ToyUI Toolkit are expected to occur in post-secondary institutions with graduate students and undergraduate students. Short-term usage evaluations are expected to happen in workshops in public or private events with professionals (e.g., designers, engineers, and computer science professionals). The secondary stakeholders (e.g., educators, therapists, children, and parents) are included in the treatment evaluation as end-users. End-users are expected to participate during all HCD stages, first, as an input for user research information (inspiration stage) and for evaluating ideas and the ToyUI prototypes (ideation and implementation stages).

Regarding the results analysis strategies, the treatment evaluation mixes different qualitative assessment methods. The preliminary evaluation of inspiration and ideation tools in 2016 sessions are available in the research article (ALBUQUERQUE; BREYER; KELNER, 2017) and Master's thesis (ALBUQUERQUE, 2017). This preliminary usage evaluation used semi-structured interviews as the post-evaluation instruments. The principal investigator interviewed a group of seven students after the two long-term sessions, and the interview transcripts supported conventional content analysis by codifying the text. After identified the proposed tools' strengths and weaknesses, short workshops with interdisciplinary creators incorporated all identified corrections in the ToyUI Toolkit. Semi-structured interviews permit assessing and individual's feedback and support identifying issues in Toolkit's usage that they might have had, also giving opportunities to clarify misconceptions (LEDO et al., 2018). Although gathering personal feedback can support understanding an individual's point of view when using the ToyUI Toolkit, more information still is necessary to identify all necessary improvements in the tools.

Direct observation helps informing how users approach the toolkit to solve problems. Problem-solving can range from closed tasks requiring a specific solution to a given problem, to open tasks where participants formulate the problem and use the toolkit to create their own solution (LEDO et al., 2018). The ToyUI Toolkit offers a collection of structured tools that permit anticipate tasks and goals during problem-solving, which can support direct observation strategies. For instance, one can observe information on the ToyUI categories, genres, toy components, play rules, data collection patterns, prototyping stickers, types of HRI tasks, setup technology, and the hardware toolkit modules used by creators in each project. For that reason, this thesis opted to employ summative content analysis strategies to assess the creators' working materials instead of the conventional approach of extracting data from the interviews in previous work.

Table 21 – Summative content analysis strategies to extract information from working materials using the ToyUI Toolkit.

HCD TOOL	EXPECTED INFORMATION AND SOURCES
ToyUI Classification	Number and types of selected features, setups, genres, and categories of each analyzed artifact, extracted from the structured classification sheets.
Brainstorming ToyUI	Number and ideas thematic in each ideation phase extracted from structured ideation sheets and presentation materials.
Data Collection Planning	Number and types of selected data collection, including PD, non-PD, sensitive data, and non-PD patterns, extracted from structured data planning sheets and diagrams.
Robot Storyboard Ideas	Number and thematic of ideas developed, considering robot model, expected data collection, and HRI tasks, extracted from the storyboard's contents.
Stickers ToyUI	Number and types of selected paper-based materials extracted from the low-fidelity prototypes (e.g., paper sensors, actuators, and data management concepts).
MiMi AI-Robot	Number and types AI features selected in the robot application and functional features from the low-cost robot embodiment, including performing vulnerability tests.
IoT4Fun Toolkit	Number and types of selected hardware modules, integrated libraries, and implemented functionalities, including performing vulnerability tests.

Source: Author.

Table 22 – A/B post-evaluation survey structure for the ToyUI Toolkit assessment.

QUESTION	**ENTRY**	**EXPECTED DATA**
The tool's name and a picture displaying the tool.	No-entry	The goal is remind stakeholders about the tools they are evaluating.
The (tool name) was easy to use	Likert-scale	Strongly agree to strongly disagree. We use it for each evaluated tool.
I would need help to use the (tool name) again.	Likert-scale	Strongly agree to strongly disagree. We use it for each evaluated tool.
I think the (tool name) helped me during the INSPIRATION stage.	Likert-scale	Strongly agree to strongly disagree. We use it for ToyUI Classification and Brainstorming ToyUI.
I think the (tool name) helped me during the IDEATION stage.	Likert-scale	Strongly agree to strongly disagree. We use it for each evaluated tool.
I think the (tool name) helped me during the IMPLEMENTATION stage.	Likert-scale	Strongly agree to strongly disagree. We use it for Storyboard Robot Ideas, Data Collection Planning, and Stickers ToyUI.
Please leave comments and suggestions, clarifying strengths and weaknesses on the (tool name)	Open-question	A list of challenges they have faced and suggestions for improvements. We use it for each evaluated tool.

Source: Author.

The summative content analysis permits assessing the HCD tools' expected goals by counting and comparing keywords extracted from creators' working materials and relating them with the problem context (e.g., ideation sheets, data models, and prototype history features) (HSIEH; SHANNON, 2005). Table 21 details the strategies adopted to extract information from stakeholders' working materials in the ToyUI Toolkit. Besides, keeping track of project advances by analyzing iterative technical documentation and requesting feedback on creators' experience in teamwork during and after the classes also supported adding valuable information to usage evaluation. The remote evaluations from 2020–2021 permitted recording weekly meetings, which facilitates qualitative assessment. The usage evaluation also considers the outcomes of usability testing of creators' projects with secondary stakeholders (e.g., children, parents, and other individuals) by consulting information provided in their user testing reports.

This thesis' final usage evaluation experiments with the A/B comparison approach using a post-evaluation Likert-scale usability survey and open questions after each assessment stage (LEDO et al., 2018). The goal is to assess if the ToyUI Toolkit is easy to use, clear to understand and if the tools are adequately distributed in the HCD stages. The A/B comparison strategy consists of stakeholders developing initial ToyUI projects following the HCD cycle without the HCD tools' assistance. Then, after a pause, the same stakeholders use the HCD tools weekly when developing new ToyUI projects in different teams. The post-evaluation survey is applied at the end of each project, and the

Table 23 – A/B post-evaluation survey for the HCD assessment.

QUESTION	**ENTRY**	**EXPECTED DATA**
Evaluate your overall experience in the (first and second) project.	Likert-scale	Ranging from very satisfied to very unsatisfied.
List at least 5 challenges encountered during the (first and second) project.	Open-question	A list of challenges they faced during each stage.
Select the HCD stage that you consider to be the most challenging in the (first and second) project.	Bullet-point	Options are inspiration, ideation, and implementation.
Support your answer with the previous item.	Open-question	A list of reasons and an explanation that reflects the challenges of each HCD stage.
How satisfied are you with the execution of the (first and second) project?	Likert-scale	Very satisfied to very unsatisfied.
What would you like to have done in the (first and second) project that was not possible to do during execution?	Open-question	A list of missing features and expectations creators had for each project the reasons they could not achieve them.
Overall, rate how satisfied you are with your team experience on the (first and second) project.	Likert-scale	Very satisfied to very unsatisfied.
List up to 5 positive and negative points about your team experience in the (first and second) project.	Open-question	A list of challenges and opportunities they faced working in teams during each stage.
Please leave your suggestions so that, if possible, we can implement improvements.	Open-question	Get feedback for improvements and suggestions.
Make a brief comparison of your overall experience during the first and second project.	Open-question	This question was included in the second survey to compare their experiences in their own words.

Source: Author.

second project evaluation includes a separate section evaluating usability aspects in the HCD tools based on the System Usability Scale (SUS) items (BANGOR; KORTUM; MILLER, 2008). Tables 22 and 23 detail the post-evaluation surveys, including the HCD evaluation section (to be used after the second project).

4.5 DISCUSSIONS

In summary, the DSM cycle started investigating the stakeholders' needs and goals to propose an adequate treatment design. The proposed treatment design supports the stakeholders' goals by intervening through different system development stages. Treatment validation distributes the proposed tools into inspiration, ideation, and implementation stages following HCD principles. The stakeholders' evaluation investigates how implemented ToyUI Toolkit interacts with the problem context in a real-world scenario in a series of case studies. Coming next, **Chapter 5** details each HCD tool, and **Chapter 6** summarizes stakeholders' evaluation results.

5 TOY USER INTERFACE TOOLKIT

This chapter details the final version of the **Toy User Interface (ToyUI) Toolkit**, considering tools' version history after stakeholders' evaluation sessions. It also proposes alternatives and strategies to adapt the Human-Centered Design (HCD) tools, supporting remote education and teamwork during the COVID-19 pandemic. The following sections focus on describing each HCD tool individually, and a separate section selects supporting tools for technical documentation and user evaluation sessions. Version history is fully discussed in the evaluation chapter.

5.1 TOYUI CLASSIFICATION TOOL

Referring to the ToyUI classification in **Chapter 2**, this tool aims to guide creators in understanding what play and interface features are available to design new ToyUI setups. The expected outcome is that creators can incorporate those features into their creative repertory, supporting them in the *Ideation* stage. In a classroom or teamwork setting, the **ToyUI Classification Tool** can support creators during the context of use definition, guiding the search for inspirational artifacts. That way, the instructor or project manager can empower creators with none or little experience with ToyUI setups and related topics, balancing their understanding level and seeking inspiration from Child-Computer Interaction (CCI) literature and industries. Table 24 describes the required steps to implement the ToyUI classification tool. This tool fits as a paper-based activity, in which creators can look at the complete list of features and select the ones that best represent evaluated items. As long as the tool supports extracting essential information from existing ToyUI setups, any format should bring similar outcomes to the creators (i.e., making a feature-based analysis of the ToyUI setups).

Alternatives for remote training include using a word processor file (e.g., *Microsoft Office Word, Open Office*, or *Google Docs*) or a slide presentation tool (e.g., *Microsoft Power Point* and *Google Slides*) to support feature selection by marking check-boxes or something similar. Creators can print or type directly in the digital files to complete individual tasks, while creators who work together can share their screens to work on local files or login into the same online file to make edits together. Another version of this tool can use an online form to select features and a spreadsheet to display results to the instructor or project manager (e.g., *Google Forms, Google Sheets*, and *Survey Monkey*). The goal of assessing classification results is to measure the creators' understanding of ToyUI features and correct or clarify any misconceptions. Finally, a custom web-based solution such as an interactive infographic can incorporate more information and multimedia resources and make the results available to other creators to see them and compare.

Table 24 – Required sections to implement the ToyUI classification tool

SECTION	CONTENT
Context of Use Information	Project title, author or team members, intended target audience, project general thematic, and and overview of project goals. A design briefing contains a list of expected stakeholders, locations, usage situations, intended outcomes, and relevance to stakeholders.
Inspirational Artifacts	A numbered list includes inspirational artifacts containing their name, sources (e.g., research papers or brands), and an overview.
Play Features	Should support selecting any applicable play features for each inspirational artifact, (i.e., general and specific play purposes, play rules, target audience including age-range, general thematic, physical and social play dynamics, and environmental aspects).
Interface Features	Should support selecting any functional interface features for each inspirational artifact, (i.e., primary toy component, its shape, size, and symbolic representation, quantity and types of secondary components, and their interactivity and connectivity aspects).
Categories, genres, and setups	Should display the complete list of ToyUI categories, genres, and setups, allowing creators to suggest new classifications.

Source: Author.

5.2 BRAINSTORMING TOYUI TOOL

Related literature suggests that inspiration to create new concepts for ToyUI setups can derive from observing children playing with traditional toys and digital games (MARCO; CEREZO; BALDASSARRI, 2012). The HCD tool for the *Ideation* stage is the **Brainstorming ToyUI**, which mixes traditional toys and play rules information to help creators generate ToyUI concepts. The Brainstorming ToyUI aims to stimulate creators to generate ideas by assembling physical toys' interface features with digital or traditional play features. The inspirational set must include a variety of toys and be preferred without brands or transmedia contents. A suggested toy set can consist of everything since balls, Frisbee, hula hoop, toy cars, dexterity toys, swords, figurines of animals (e.g., sea animals, mammals, and insects), dominos, chessboard, and so on. The set of play rules must be simple and straightforward, displaying short descriptions for closed-play rules (e.g., runner and tower defense) and open-ended play rules (e.g., hide and seek, hotchpotch, and tag). What differs closed-play from open-ended play rules is that open-ended play rules allow participants to regulate or negotiate rules during playtimes, such as assembling teams, turns, and the number of chances (SOUTE et al., 2017). In that way, the ToyUI setup does not necessarily have to manage and account for all play behaviors during CCI.

The Brainstorming ToyUI focuses on mediating the communication between interdisciplinary teams, which still is challenging. It can support group discussion by involving all participants since the early concepts by not separating designers from developers when expressing their impressions. The general structure is based on the *Discussion 66* technique, which consists of distributing participants into small groups to discuss ideas following a sequence of statements or questions (DENTON; DENTON, 1999). This technique proposes shifting the groups' participants to stimulate an exchange of views and avoid creators to fixate on a single idea. The Brainstorming ToyUI is better performed in groups of 3-6 participants and by exchanging both creators and toy resources. A larger group can become a challenge to manage. Some creators may find it defying to speak up while conducting the ideation in pairs can limit discussion diversity since one participant must act as the session *reporter*.

In overview, short sessions include an 18 minutes opening session, three or more exchanging sessions (6 minutes), and a 12 minutes closing session (that reunites the initial group). After the timing, the *mediator* (e.g., class instructor or project manager) must exchange one or two participants and one or two toy resources. Exchanges in the groups can follow simple rules (e.g., professional background, age, or gender identity). The entire group discusses one toy each time in the short sessions by following a structured ideation sheet. The sheet contains sections to detail different toy aspects: physical, interactive, and semantic attributes (e.g., materials, functionalities, and narrative or emotional characteristics related to play, respectively). After describing the toy sample, the group should sort one or more play rules cards to generate ideas. One creator, assigned as the *reporter*, has to compile all identified attributes in the ideation sheet.

After the closing session, all ideation sheets must be assembled and arranged according to the toy components they describe. After organizing them, the creators receive the sheets back to recycle ideas (similar sheets must stay together). This ideation session aims to improve the quality of ideas by applying creative constraints to them. Recycling ideas occurs by adding one or more creative constraints to the initial concepts, and this session can occur in groups, pairs, or individually. Creative constraints consist of items based on the context of use definition. For example, when the context of use determines gender, age, or any aspect related to a ToyUI setup, genre, or category of the ToyUI classification, the list of constraints must address this specific context. They must be preferably planned through user research techniques (e.g., personas, use cases). For instance, the mediator can request creators to list some items shortly after the ToyUI Classification tool practice.

Creative constraints must be simple and straightforward to support creators when improving initial concepts. The list of creative constraints can cover specific themes, educational topics, transmedia characters, and other marketing indicators in a marketing-oriented context. Table 25 distributes a sample list of creative constraints for ToyUI design into three groups: *Context-driven, Play-driven,* and *Content-driven*. Context-driven items address information related to the target audience and interaction environment (e.g., age group, special needs, indoor or outdoor environment). Play-driven items cover aspects related to the expected play rules and dynamics (e.g., play modalities). Content-driven items address aspects related to the general or specific purposes of the ToyUI setups (e.g., education, therapy, or physical exertion).

Table 25 – Creative constraints samples for the Brainstorming ToyUI

CONTEXT-DRIVEN	**PLAY-DRIVEN**	**CONTENT-DRIVEN**
The idea includes two age groups of end-users.	The idea collects only two types of data.	The idea promotes learning through play.
The idea offers accessibility.	The idea has at least two toy components in the interface.	The idea promotes therapy or rehabilitation.
The idea is gender-neutral.	The idea supports at least two social interaction modalities.	The idea focuses on narrative elements.
The idea supports indoor and outdoor play.	The idea has a toy component with attachable parts.	The idea supports editing contents.

Source: Author.

The Brainstorming ToyUI tool is practically suitable for face-to-face sessions. Strategies to conduct the sessions during online education or remote teamwork settings are discussed as follows. The first challenge is turning paper-based and tangible resources into digital resources (i.e., the brainstorming sheets, recycling sheets, physical toys, and play rules card sets). Initially, the brainstorming sheets can use similar strategies to the ToyUI classification tool using local or online word processing tools. However, the recycling sheets for the creative constraint practice would fit a slide presentation tool or sketching tool that permits drawing or using geometric shapes to represent the ideas, preferably a collaborative tool like *Google Slides* or *Sketchpad*.

Concerning the tangible resources, physical toys need to be presented in a way that permits extracting their physical, interactive, and semantic attributes. An alternative is to turn the physical toy set into a digital card set. The toy card set must include a picture of the physical toy and display sufficient information on physical properties (e.g., size, materials, and description of moving or attachable parts). The digital and paper-based versions of the play rules card set can stay essentially the same, as for sorting them, the cards can be labeled or numbered to some kind in an online randomizer tool (e.g., *Random.org*). Alternatives include the mediator sharing separate folders with the participants, containing different resources, or deleting or adding resources from the shared folders in real-time (e.g., *Google Drive, Google Classroom*, or *Dropbox*).

Another essential aspect is to support group discussion, so it is necessary to establish an online chat among participants, preferably using video or audio. The main challenges include selecting an online chat platform that supports monitoring, distributing, and exchanging the participants in separate groups. In a teamwork session with fewer participants, creators can use a standard online chat, and the mediator can act as the reporter and exchanging the digital resources. However, it is essential to distribute participants into small groups (3-6 participants) in a classroom session. The online chat platforms *Zoom* and *Google Meeting* offer a feature called *Breakout Rooms*. The host can automatically split the participants into small groups, exchange participants between groups, and time the sessions. Both platforms are free to use with limited features, but the breakout feature is not included. There are also community *Google Chrome* extensions that permit performing similar breakout rooms in the *Google Meeting* platform. The paid web platform *Remo* can also be an alternative, which is suitable for conducting online webinars and conferences and does not require downloading software on the personal computer.

5.3 DATA COLLECTION PLANNING TOOL

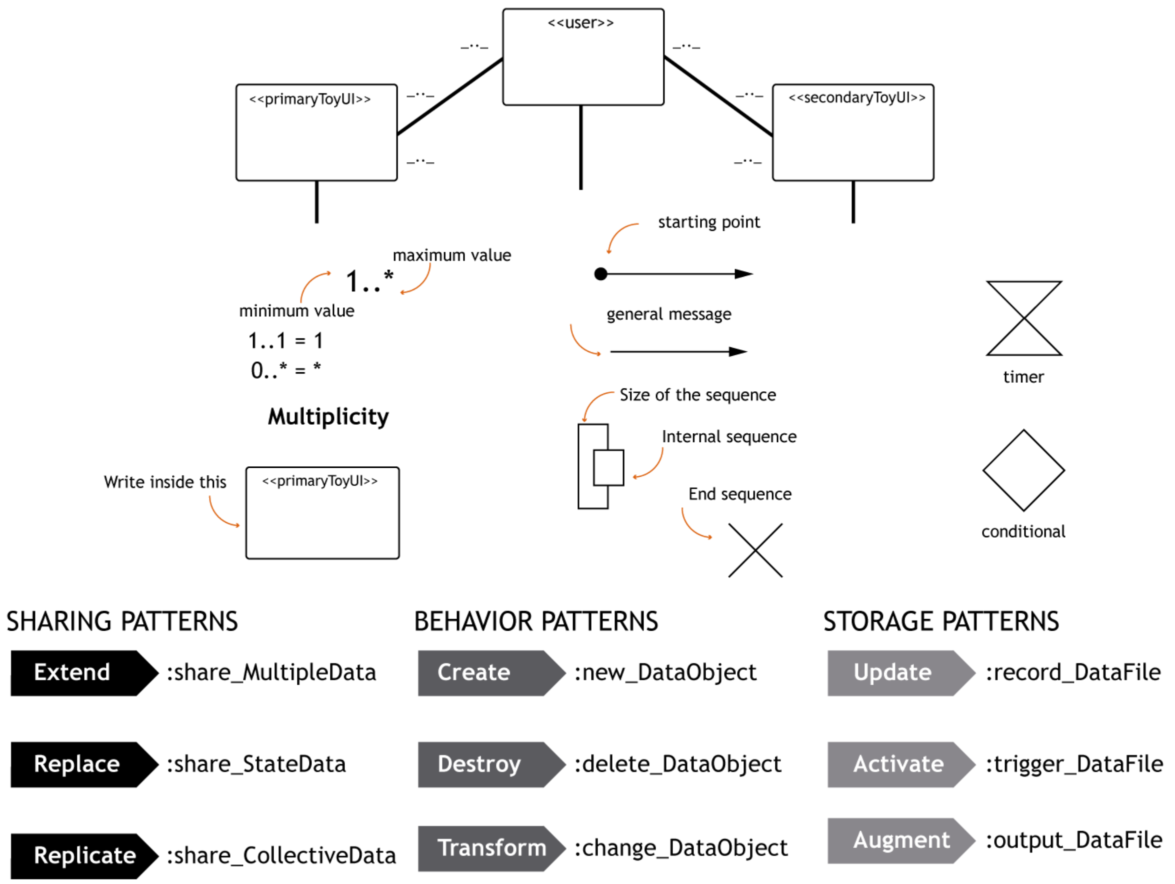
The **Data Collection Planning Tool** aims to minimize selecting ideas that can potentially introduce privacy risks to CCI by prioritizing non-Personal Data (PD) collection strategies (ALBUQUERQUE; KELNER, 2019). This tool can be introduced as early as the *Ideation* stage, and it can also be used and updated by the teams through different *Implementation* cycles. The data collection planning tool comprises two stages. The first stage consists of creators choosing one or two ideas (preferably from the Brainstorming ToyUI sessions) to pick what type of data they expect that the idea will collect. A table sheet organizes the types of data into three groups.

- Non-PD collection includes Non-Personal Identification (NPID), Unidentifiable Positioning System (UPS), and motion tracking information.
- PD collection covers data like voice, facial pictures, bio-data, Global Positioning System (GPS), and other user profile information (e.g., full name, e-mail address, and billing information).
- Sensitive data collection includes multimedia files related to objects (e.g., pictures or videos of markerless or marked objects with fiducial markers or QR codes).

ToyUI setups must only collect data that is essential to CCI. When using the data planning tool, if any PD or sensitive data type is selected to fulfill the idea, creators must choose a non-PD type to use it alternatively (when applicable). In that way, they can first reflect if collecting PD is essential or not to their initial concepts. For example, a creator may first select to collect multimedia information from an object to support object identification. Multimedia information from objects is classified as sensitive since data collection may include unexpected information from the user or environment while using the camera or microphone (ALBUQUERQUE; KELNER, 2019). After reviewing the non-PD options, they may find that selecting NPID can better suit their idea instead.

After this stage, only similar or duplicate ideas should move to the second stage (i.e., same idea sheet or different ideas related to the same ToyUI component). Creators can

Figure 13 – UML-like diagram and notations for non-PD planning



Source: Author.

work with their initial ideas or pick-up other ideas to work on as long as they have moved forward. The second stage of the data collection planning tool consists of filling the data collection diagram sheet. The data collection diagram aims to plan CCI according to the set of play rules of each idea. Therefore, the idea sheet must contain an initial set of play rules defined (i.e., closed-play or open-ended play rules). The diagram can relate users and two ToyUI components each time (e.g., the child, toy component, and companion device component). The creators can plan data collection and data exchanges among hardware and software components using this tool.

In Figure 13, the diagram incorporates the set of non-PD collection patterns and other notations inspired by the UML class, sequence, and activity diagrams (UML; MOF, 2011). The non-PD patterns were previously described in Table 14 in **Chapter 2**. As a descriptive example of using the UML-like notations, a creator starts naming the primary and secondary ToyUI components using the respective class boxes. Next, he/she uses the multiplicity notations to define the number of components and users and how they relate to each other. Then, using the activity notations, the creator can detail data exchanges between each component. The non-PD patterns permit setting a sharing mode between components, such as replicating information. Individual data exchanges result in data behavior patterns (e.g., creating new data files or transforming existing values). Finally, the storage patterns support defining a temporary storage type of each data behavior (e.g., updating information or triggering a single event).

After completing the non-PD collection diagram, it is expected that all planned ideas are suitable to move to the implementation stage. Creators can use the planning diagram at this stage to start technical documentation and keep track of changes during the iterations. Once more, both the data types sheet and planning diagram sheet are initially paper-based. Alternatives for digital versions include using word processing or spreadsheet tools for the first sheet and a flowchart or diagram tool for the second. Examples of collaborative diagram tools are *Lucidchart* and *Draw.IO*, and the last includes integrated applications for *Google G Suite* and *Gooogle Chrome, Confluence*, and *Microsoft*.

5.4 STORYBOARD ROBOT IDEAS TOOL

Planning the Human-Robot Interaction (HRI) tasks is essential to support creators during the *Implementation* stage. Previously, authors proposed using sketched storyboards to plan HRI behaviors, which proved to be a fast and helpful way for teams to discuss robot behaviors and quickly decide which behaviors to be implemented on the robot (MEERBEEK; SAERBECK; BARTNECK, 2009). Paper-based sketches can present some limitations for creators, such as sketching movements and sounds, among other HRI behaviors. Creators can usually simulate those behaviors later using a 3D robot simulator (when available) or a rapid prototyping tool (e.g., block coding robot simulator). The **Robot Storyboard Ideas Tool** consists of a digital storyboard resource that offers specific robot embodiment information to creators. From 2019–2020, one implemented three storyboard templates to test with stakeholders using different robot models. Table 26 compares each robot model, and Figure 14 compares sections of the templates.

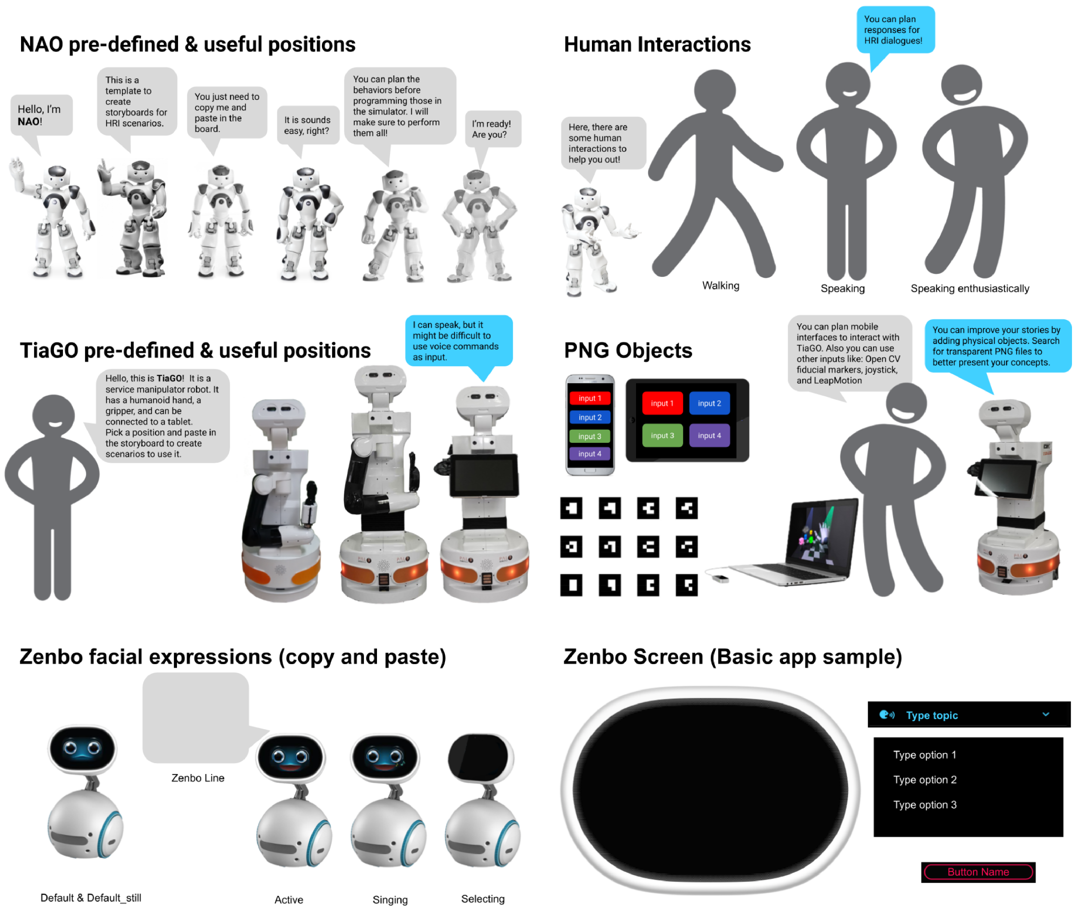
Introducing this tool in the *Ideation* stage can support quick sketching of ideas, group discussion, and careful planning of robot behavior during initial prototyping stages. The instructor or project manager must prepare the robot storyboard ideas templates before introducing them to the creators to incorporate precise information on the robot model embodiment. In a general structure, to build a robot storyboard idea template for any robot model, it is needed to get information on the robot's embodiment functions. The templates use the *Google Slide* platform and editing transparent PNG files found online to create the scenes. The slide presentation tool offers features such as typing dialogues in balloons, basic animation, and support to insert multimedia files (e.g., videos from *YouTube* and animated GIF files). This digital tool suits in-person or remote and individual or collaborative activities, and it can be used from early to advanced stages of ideation, planning of HRI tasks before implementation, and presenting the HRI solutions to an audience (e.g., team, classroom, or investors).

Table 26 – Overview of robot embodiment features of each robot model.

ROBOT	EMBODIMENT FEATURES
NAO V5 (SoftBank, 2014—2018)	**Sensory:** Loudspeakers, microphones, video cameras, Force Sensing Resistors (FSR), Inertial Measurement Unit (IMU), sonars, joint position sensors, contact and tactile sensors. **Connectivity:** Ethernet, Wi-Fi, and USB. **Emotion:** Static. **Movement:** Head, shoulder, elbow, wrist, hand (actuated hands and fingers), hip, knee, and ankle. **Displays:** RGB Light-Emitting Diode (LED) on head, eyes, ears, and chest.
TIAGo (PAL Robotics, 2021)	**Sensory:** Laser, rear sonars, IMU 6 Degrees of Freedom (DoF), RGB-D camera, audio speaker, microphones. **Connectivity:** Wi-Fi and Bluetooth 4.0. **Emotion:** Static. **Movement:** Head, neck, articulated arm (7 DoF), actuated hand/grip, torso, and base. **Displays:** Attachable tablet/PC, base (LED)
Zenbo (and Zenbo Junior) (ASUS, 2016—2021)	**Sensory:** Digital microphone, 13M Camera, speaker, drop Infrared (IR) sensor, Consumer IR (CIR) sensor, sonar sensor, line sensor, capacitive touch sensor. **Connectivity:** Wi-Fi and Bluetooth 4.0. **Emotion:** 24 cartoon facial expressions. **Movement:** Head, neck, and base. **Displays:** 12.6-inch touchscreen (6-inch Zenbo Junior) and wheels (RGB LED)

Source: https://www.softbankrobotics.com/, https://pal-robotics.com/robots/tiago/, https://zenbo.asus.com/.

Figure 14 – Storyboard templates featuring different robot embodiment functions.

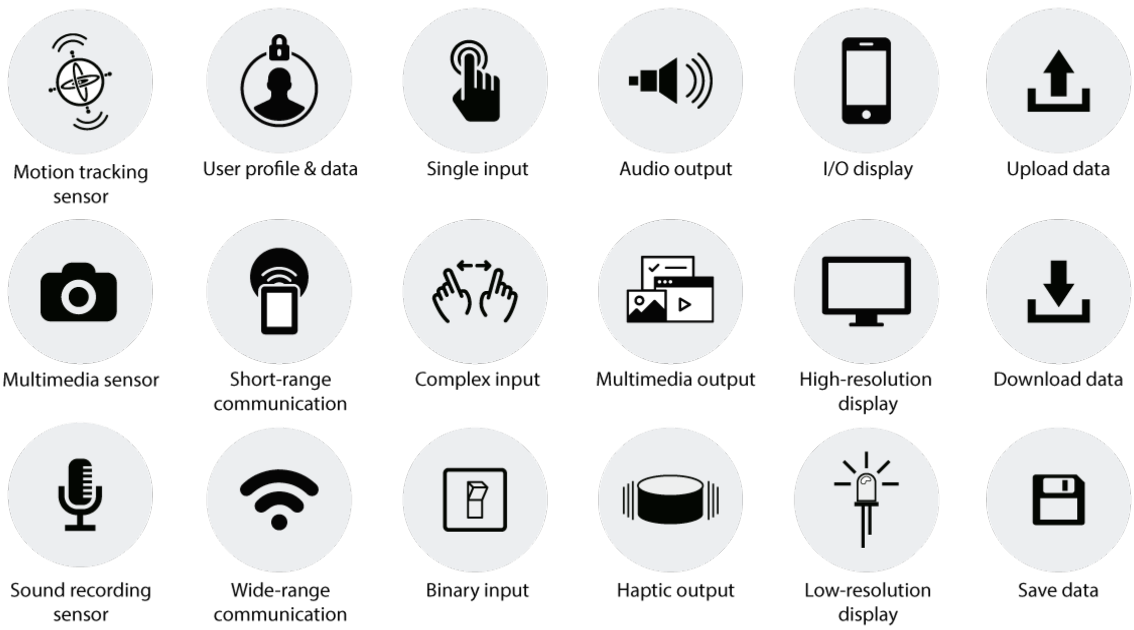


Source: Author.

5.5 STICKERS TOYUI TOOL

Low-fidelity prototyping of CCI systems can become challenging to creators, mainly when translating interactive aspects into static and abstract concepts. A low-fidelity prototyping tool for ToyUI setups can combine traditional physical toys with office and crafting materials like papers, colored pens, scissors, tapes, and cardboard. A collection of **ToyUI Stickers** represent different sensors, communication protocols, inputs and outputs, displays, and data storage behaviors to facilitate the practice. This design tool aims to simplify technological and interactive aspects to help the teams first prototyping the interface features of the ToyUI setup in the early *Implementation* stage. In that way, attaching the stickers to a ToyUI component may help them plan and test the concepts. For instance, a motion-tracking sensor sticker attached to a toy can mean that the toy component can collect 3D positioning and orientation. Then, adding a short-range communication sticker to a doll and the same sticker to a food toy will mimic the doll eating the food toy through contactless identification. Also, attaching a low-resolution display sticker to the doll's chest can represent the output to augment visual feedback for the mimicked behavior. Figure 15 shows the collection of stickers available to attach into low-fidelity prototypes of ToyUI setups.

Figure 15 – ToyUI Stickers collection for low-fidelity prototyping of ToyUI setups.



Source: Author.

The ToyUI stickers work during face-to-face sessions, in which the teams can use tangible resources like physical toys and other paper and office materials. The challenges of transitioning these resources to a remote setting include the availability of materials, particularly the physical toys at the participant's location. Although the stickers can be easily printed at home and attached to available physical objects to represent interface tokens, more resources are still necessary to support all desired interface features in a ToyUI setup. Paper prototyping software like the *Pepakura Designer* and traditional origami techniques can help creators designing a paper embodiment and distributing the ToyUI stickers into it. Many paper-based 3D models are also available to download for free online on designer's websites (e.g., *Paper Foldables* and *Fold Up Toys*). The instructor or project manager can also send printable templates, including some recommended sensors, such as those restricted to support the non-PD collection approach (e.g., motion sensor, wide and short-range communication protocols, low-resolution display, speaker, and vibrating motor). The printable templates can be developed in vector graphics software such as *Adobe Illustrator, Corel Draw, GIMP,* and *Inkspace.* A complete digital alternative include translating the stickers into digital badges to support visually describing the ToyUI components. It can use a slide presentation tool (e.g., *Power Point* or *Google Slides*), permitting integrating this tool with the Robot Storyboard Ideas templates.

5.6 MIMI AI ROBOT TOOL

Robot embodiment defines the constraints in which creators can develop HRI solutions. **MiMi AI Robot** low-cost robot embodiment and an integrated Artificial Intelligence (AI) application using open-source resources to offer HRI features to integrated CCI applications. MiMi is a participatory design project developed by this thesis' principal investigator, the *Virtual Reality and Multimedia Research Group (GRVM)* team, and graduate students from the Computer Science Graduate Program at *Universidade Federal de Pernambuco (UFPE)* Brazil. One defined MiMi AI Robot's design concept and system architecture in five essential modules: vision, voice, communication, expression, and content modules. The vision and voice modules provide multimedia input/output supporting user, object, environmental recognition, and voice-based interaction. The communication module regulates data packages and exchanges between all modules and provides access to physical embodiment functions. The expression module provides output for robot emotion. Finally, the content module is an external module that supports integrating play activities and other content using a connected application. The GRVM developed the low-cost robot embodiment for the *Implementation* stage, using a set of essential hardware components, such as servo and Direct Current (DC) motors, ultrasound sensors, RGB LED, and a microcontroller connected to a smartphone using a USB-C port. We fabricated the internal structure using metal in a Computer Numerical Control (CNC) machine, and we designed a paper robot embodiment in the software *Pepakura Designer.* The MiMi character design is an anthropomorphic cat-like robot, and a soft white material covers the paper embodiment to a finished look. Together with the UFPE students, we developed an initial *Android* app that runs in a smartphone connected to the robot's head.

The first MiMi AI app displays robot emotion using animated cartoon facial expressions (GIF files) developed by our research team. This version supports native *Android* text-to-speech and speech-to-text functions and uses multimedia input from the smartphone's built-in microphone and frontal camera. A companion application connects to the primary smartphone to control the robot embodiment and support CCI content. The dialogue system uses cloud processing through *Google's* natural language platform *DialogFlow* and the *Snowboy* API from *Kitt.AI* to set the *hotword* – Hi, MiMi. We integrated machine learning models using *TensorFlow Lite* to support offline processing while detecting a set of objects and recognizing users. A new set of animated facial expressions are short clips designed in the *Adobe After Effects* software. They follow (SCHERER, 1987) psychological emotion theory and guidelines from related works on robot emotion and virtual social agents (GRIZARD; LISETTI, 2006; KORN; STAMM; MOECKL, 2017; BREEMEN; YAN; MEERBEEK, 2005). A new dialogue system uses the *IBM Watson Assistant* and reviews security requirements and applicable privacy policies (SHASHA et al., 2018). Future versions will integrate the MiMi AI app with this thesis' rapid prototyping tool and a 3D animated simulator for robot embodiment to support remote training. The strategies for this integration will be discussed in the following subsection.

5.7 IOT4FUN TOOLKIT

Rapid prototyping tools permit fast high-fidelity *Implementation* and testing of the ToyUI setups. Over the years, this thesis has developed and improved three versions of the **IoT4Fun Toolkit**. The IoT4Fun Toolkit goals are to support the implementation of ToyUI setups across all categories and genres, facilitating hardware–software integration aspects, and implementing non-PD collection strategies. An adequate rapid prototyping tool for ToyUI design must provide full adaptability (1), offer distributed data collection (2), multimodal user feedback (3), editing of play features (4), and limit PD collection (5) (WHELER et al., 2020).

Firstly, a prototyping tool can achieve full adaptability (1) by fitting into different designs without compromising its usage and essential functionalities. Printed Circuit Board (PCB) manufacturing supports the development of custom circuit solutions that can minimize the use of wires, resistors, capacitors, and inductors. Modularity facilitates distributing the hardware components into each toy component respecting its physical restrictions (DESAI; MCCANN; COROS, 2018), allowing creators to select components they need for each projects (KAZEMITABAAR et al., 2017). Also, connecting hardware components using "plug-and-play" or stackable approaches can help deliver an easy-to-use tool for the creators (WANG et al., 2016).

Secondly, toy components by themselves may offer limited computational capacity, so they often connect with more powerful computing devices like smartphones, tablets, game consoles, and companion robots to share those capabilities (RAFFERTY et al., 2017). Distributed communication channels (2) can support transferring data between the toy component and other ToyUI components using short-range and long-range communication protocols (e.g., Near-Field Communication (NFC)/Radio Frequency Identification (RFID), Wi-Fi, Bluetooth, Bluetooth Low Energy (BLE), and other Radio Frequency (RF) protocols).

Thirdly, ToyUI setups must provide continuous feedback to the player's actions, and feedback modalities include visual, auditory, and tactile feedback (SOUTE et al., 2017). Multimodal feedback (3) must also respect the distributed aspects by appearing in the primary and secondary ToyUI components. Visual feedback in the toy component can use low-resolution displays such as LED panels. Auditory feedback can use essential solutions like buzzers or small-sized speakers enabled to reproduce from 8-bit to MP3 audio files. Tactile feedback include using vibration motors and other servo or DC motors. More sophisticated feedback can use connected devices and companion robots to support high-quality displays and speakers, and performing HRI tasks.

ToyUI setups mix play features from traditional toys and games to support CCI experiences, resulting in multiple social and physical play modalities. Play modalities include social competition, collaboration, parallel play, physical manipulation, and full-body interaction. Open-ended play rules and closed-play rules regulate these social modalities and the prototyping tools must support creators on (4) fully implementing them. Adopting a robust Integrated Development Environment (IDE) can facilitate implementing play features – the *Arduino* IDE offers a cross-platform application with free-software licenses compatible with several *Arduino* and third-party boards, supporting programming languages C and C++, many libraries, and has an extensive development community. Libraries can support integration with 3D and 2D game engines, and developing integrated mobile applications.

Finally, microcontroller technology is still facing challenges to ensure sufficient security against data-breach and other vulnerabilities due to limited processing capabilities. For the sake of security, (5) the toy component must limit data collection to non-PD (ALBUQUERQUE; KELNER, 2019). PD can be gathered using secondary ToyUI components since they offer adequate infrastructure for data security. Creators can use NPID, UPS, and Motion Tracking information to design various play rules and dynamics. Sensors like accelerometers, gyroscopes, magnetometers, and barometers can collect the required motion tracking data to support CCI. Besides, by combining long and short-range wireless communication protocols the rapid prototyping tool can support Local Positioning System (LPS). Limiting PD collection does not minimize the need for adequate privacy policies and data security approaches (ALBUQUERQUE et al., 2020). In that way, all communication between the ToyUI components must comply with data security standards and privacy protection regulations.

Table 27 compares the IoT4Fun Toolkit with other hardware toolkits from related works according to these five essential aspects (1–5), and Table 28 compares its history version. In general aspects, the IoT4Fun Toolkit is a hardware toolkit that allows real-time motion tracking information, supports wireless communication with devices, contactless identification of objects and users, and is fully programmable using the *Arduino* IDE. IoT4Fun toolkits use PCB manufacturing to favor miniaturization and robustness while offering visual, auditory, and tactile feedback. Starting from the 2018 version, the IoT4Fun Toolkit attaches modular PCBs using flex-ribbon cables to facilitate distributing the hardware components into different ToyUI embodiments. The IoT4Fun toolkits proposed in this thesis were implemented in collaboration with GRVM researchers. One proposed and defined the IoT4Fun toolkit architecture and each module, including hardware specification, and supervised undergraduate interns in the fabrication and testing of each version.

Table 27 – Comparing how prototyping tools fully (F), partially (P), or not (N) meet the five essential aspects (1—5).

RAPID PROTOTYPING TOOL	**1**	**2**	**3**	**4**	**5**
IoT4Fun Toolkit 2020 (WHELER et al., 2021)	F	F	F	F	F
RaPIDO (SOUTE et al., 2017)	N	P	F	P	F
Body Bug (SEGURA et al., 2013)	N	N	P	P	F
Sifteo Cubes (MERRILL; SUN; KALANITHI, 2012)	N	P	F	F	F
Sketching LEGO (GOHLKE; HLATKY; JONG, 2015)	P	N	N	P	N
NIK Vision (MARCO; CEREZO; BALDASSARRI, 2012)	P	N	N	P	N
EagleSense (WU; HOUBEN; MARQUARDT, 2017)	N	N	N	P	P
JUGUEMOS (BONILLO; MARCO; CEREZO, 2019)	P	F	F	P	N
TouchToken (APPERT et al., 2018)	P	N	N	P	F
TriPOD (FUCCIO; SIANO; MARCO, 2017)	P	N	N	P	F
Widgets (BECH et al., 2016)	P	N	N	P	F
Flexibles (SCHMITZ et al., 2017)	P	N	N	P	F
WiSh (JIN et al., 2018)	F	P	N	P	F
CircuitStack (WANG et al., 2016)	P	F	F	P	N
MakeWear (KAZEMITABAAR et al., 2017)	P	N	P	P	F
DermaPad (RATHFELDER; HIPP, 2019)	P	F	F	F	N
Baby Tango (BERZOWSKA et al., 2019)	P	N	F	F	F
BBC micro:bit (KNOWLES et al., 2019)	P	F	P	P	F
SAM Labs (SAM Labs, 2021)	P	F	F	P	P
Crazy Circuits (Brown Dog Gadgets, 2021)	P	F	F	P	P

Source: Author.

Technical analysis of the 2018 version highlighted a series of necessary improvements on miniaturization, battery consumption, and reliability aspects (WHELER et al., 2020).

Table 28 – Version history of the IoT4Fun Toolkit for ToyUI setups.

VERSION	**TECHNICAL SPECIFICATION**
2017	A single PCB incorporates an *Arduino Mini-Pro*, 6 DoF IMU sensor, 3 RGB LED, a buzzer, and a battery. The communication interfaces offer short-range and long-range protocols (NFC/RFID and Wi-Fi)
2018	8 PCB modules attach using flex ribbon cables (Arduino Mini-Pro + 10 DoF IMU sensor, 3 RGB LED, speaker, vibration motor, battery, and USB recording module). The communication modules offer short-range and long-range protocols (NFC/RFID and Bluetooth/BLE)
2020	8 PCB modules attach using flex ribbon cables (Arduino Mini-Pro + 6 DoF IMU sensor, RGB Surface Mounted Device (SMD), MP3+speaker, vibration motor, battery, and USB recording module). The communication modules offer short-range and long-range protocols (NFC/RFID, Bluetooth/BLE, and Wi-Fi)

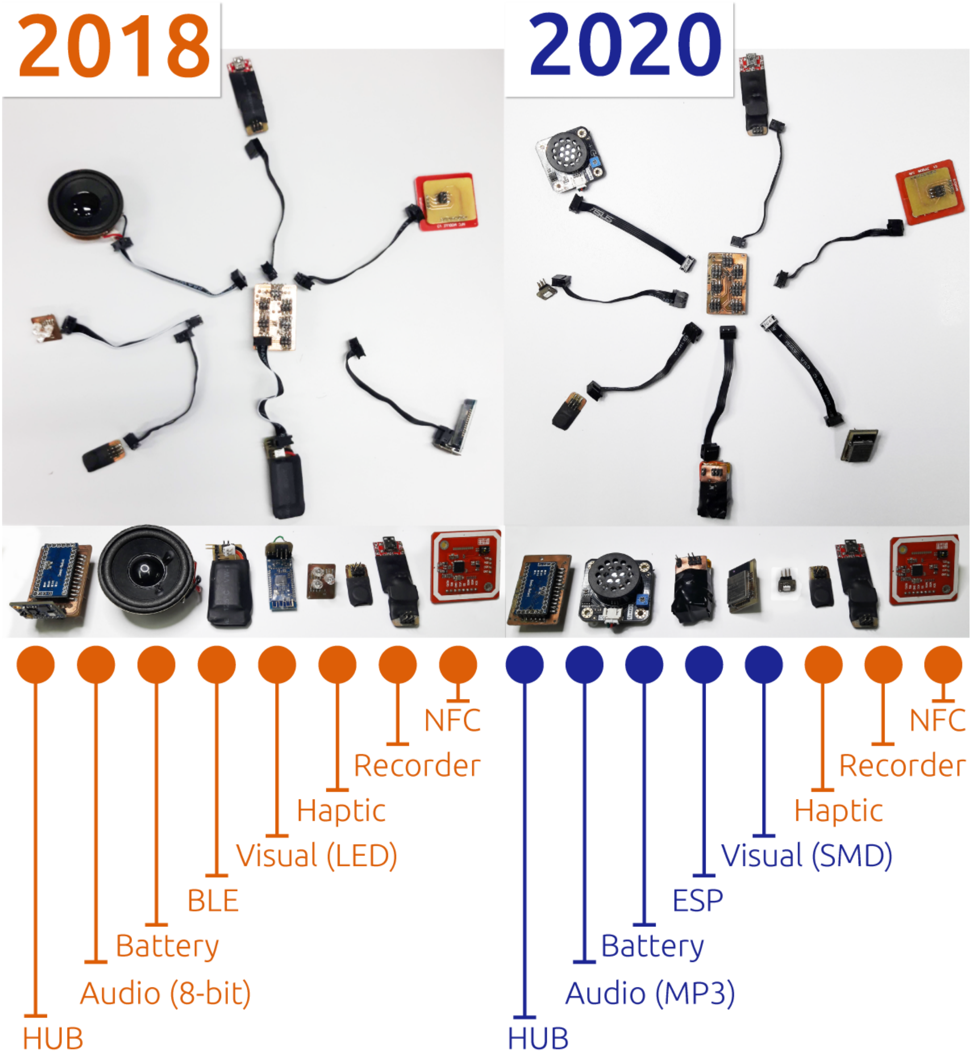
Source: Author.

Changes were necessary for the hub, audio, battery, visual, and long-range communication modules of the most recent toolkit version (2020). Figure 16 compares the 2018 and 2020 versions. First, to improve miniaturization, the goals were to incorporate the hardware components into the PCB design by incorporating the shields directly in the PCB modules and replacing some of the hardware components to improve features while reducing their size. In the 2020 version, the hub module incorporates the motion-tracking sensor shield in the PCB design, reducing its overall size. Initially, we intended to replace the Central Unit (CU) – an *Arduino Mini Pro* – to incorporate an *ATMEGA* shield as the new CU. However, available PCB manufacturing quality prevented us from welding it properly, and after several attempts, this improvement will support future versions.

The 2020 version successfully replaces the 8-bit speaker with an MP3 module attached to a smaller speaker — this module now contains internal memory to store the audio files separate from the CU. It also replaces the 3 RGB LED with a single SMD, conquering more brightness and significantly reducing the module's size. Furthermore, we exchanged the BLE module to use an *ESP32* shield, which supports alternating between Wi-Fi and Bluetooth/BLE connectivity, allowing more alternatives for creators to set up wireless communication with secondary ToyUI components. We also created a 3D-printed case to protect the hub module and connectors from damage during collisions. The protective case also indicates the adequate connector for each peripheral module.

Moreover, in the 2018 version, the battery module used a 3.7 V 350 mAh Li-Po battery and a linear regulator for the Integrated Circuit (IC) *AMS1117 3.3* for supplying a maximum of 3.3 V for the components connected to the hub module. This battery can reach up to 4.2 V when fully charged, and the cut-off voltage is 3 V when discharged. Also, considering that the battery module demands a higher current consumption when the hub module attaches to other modules, a deregulation occurred in the IC while the

Figure 16 – Comparison between 2018 and 2020 versions of the IoT4Fun Toolkit – the modules in orange remained the same.



Source: Author.

battery was discharging, affecting the toolkit's basic functionalities. In the 2020 version, we replaced the previous IC from linear to direct current (DC-DC) voltage converter using the IC *TSP62260DDCT*. This IC keeps the voltage regulated as long as the input voltage is greater than the output voltage, and the current consumption of the powered circuit does not exceed 600 mAh. The new battery module also ended-up smaller than 2018 one.

A development tool should support secure hardware–software integration for the 2020 version. The *Android* application named Rapid Coding Tool (RCT) gives access to all IoT4Fun Toolkit functions to load and edit each module's existing coding scripts and pre-sets. Table 29 shows the list of defined features on the RCT Software Development Kit (SDK). The RCT SDK also integrates the MiMi AI module to support implementing a range of interactive social toys and HRI features using the MiMi robot embodiment in future works. The RCT SDK can support remote education and teamwork since it is compatible with the *Android Studio Emulator*. In that way, creators can implement selected behaviors without necessarily having the hardware toolkit available to test them. Then, at first, the instructor can test the behaviors online and demonstrate them. Although the situation is not ideal, this solution, together with the other HCD tools, can still permit creators to transition from inspiration to ideation, data collection planning, and implementation of the ToyUI setups. In a more desirable scenario, the IoT4Fun Toolkit would be sent to the creators depending on resource availability to build and ship the units. The 2020 version unit costs up to $200 (American Dollars) but large-scale fabrication and distribution strategies are the scope of future works.

Table 29 – RCT functions according to each hardware module.

MODULE	RCT FUNCTIONS
Hub + Motion	Download and upload scripts in the CU, 6 DOF face selector, and a pre-set of linear-axis and circular motion patterns.
ESP	Find, authenticate, and connect/disconnect with any available hub module wirelessly.
NFC	Read or edit existing NFC tags, and record new tags to associate with NPIDs.
Visual	Set RGB color (HEX) and select brightness mode to the SMD (e.g., static, breathing, or blinking).
Audio	Select and play audio file from the existing playlist.
Motor	Set time and mode for the vibrating motor (e.g., single, continuous, or accelerating).
MiMi AI Robot	Manual and automated access to navigation and head movements, select facial expressions, and select existing or import new dialogues files and machine learning models.

Source: Author.

5.8 SUPPORTING TOOLS

Finally, the proposed HCD tools can guide interdisciplinary creators through all stages of system development. This thesis selects supporting tools adapted from related literature to support creators' technical documentation and user evaluation sessions. First, the **ToyUI Design Document** supports iterative technical documentation by detailing user research information, interface components, play rules and dynamics, tracking of version and prototyping history, and user evaluation reports. This tool consists of a documentation template following the general structure of a Game Design Document (GDD) (RYAN, 1999) (e.g., introduction, background, description, key features, genre, platform, concept art, etc.) but introducing specific sections to include information on all HCD tools (e.g., the ToyUI classification, play and interface features, and non-PD modelling).

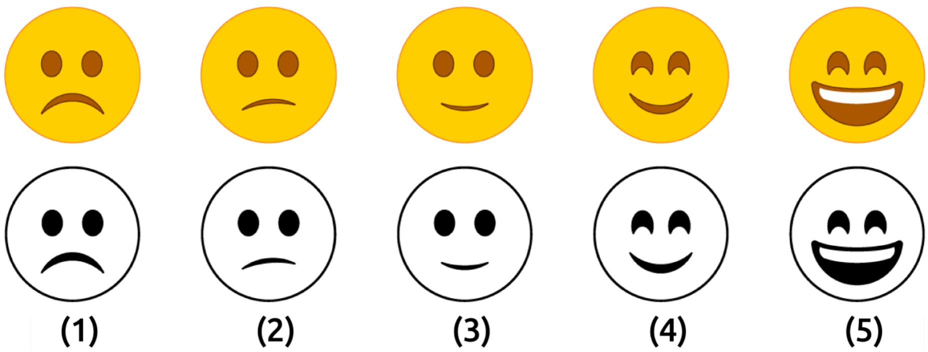
Second, this thesis selected two user evaluation tools to support stakeholders: the SUS (BANGOR; KORTUM; MILLER, 2008) and its adapted version for children — the SUS-Kids (PUTNAM et al., 2020). The SUS questionnaire consists of a list of ten affirmations

Table 30 – SUS and SUS-Kids usability affirmations.

SUS	SUS-KIDS
I think that I would like to use this system frequently	If I had this [app] on my iPad, I think that I would like to play it a lot
I found the system unnecessarily complex	I was confused many times when I was playing [app]
I thought the system was easy to use	I thought [app] was easy to use
I think that I would need the support of a technical person to be able to use this system	I would need help from an adult to continue to play [app]
I found the various functions in this system were well integrated	I always felt like I knew what to do next when I played [app]
I thought there was too much inconsistency in this system	Some of the things I had to do when playing [app] did not make sense
I would imagine that most people would learn to use this system very quickly	I think most of my friends could learn to play [app] very quickly
I found the system very cumbersome to use	Some of the things I had to do to play [app] were kind of weird
I felt very confident using the system	I was confident when I was playing [app]
I needed to learn a lot of things before I could get going with this system	I had to learn a lot of things before playing [app] well
–	I really enjoyed playing [app]
–	If we had more time, I would keep playing [app]
–	I plan on telling my friends about [app]

Source: (BANGOR; KORTUM; MILLER, 2008; PUTNAM et al., 2020)

Figure 17 – Emoji Likert-Scale for the SUS-Kids.



Source: Author.

related to system usability aspects. The SUS-Kids adapts the ten affirmations for children communication level, and adds three other statements related to enjoyment and likeability aspects (ZAMAN; ABEELE, 2010; READ; MACFARLANE; CASEY, 2002). Table 30 compare the SUS and SUS-Kids affirmations. In Figure 17, this thesis also proposes the **Emoji Likert-Scale** to use with the SUS-Kids following related work recommendations (ZAMAN; ABEELE, 2010; READ; MACFARLANE; CASEY, 2002). The Likert-scale for the SUS and

SUS-Kids questionnaires vary from strongly disagree (1) to strongly agree (5), and the SUS-Kids adds facial expressions to facilitate children's evaluation.

5.9 DISCUSSIONS

This chapter provides a detailed description of the ToyUI Toolkit to support interdisciplinary creators from the CCI research community and industries. The HCD tools include a classification tool, brainstorming and low-fidelity prototyping resources, non-PD collection and HRI planning tools, and implementation tools to support the design of integrated ToyUI components – a hardware toolkit, a low-cost robot embodiment, and an open-source AI-based application. This chapter also presented a remote training implementation and teamwork alternatives and a selection to supporting technical documentation and user evaluation tools with children and adults. The following chapter details the evaluation of all HCD tools with stakeholders. A reminder that the contents of this chapter are published in the following research papers (ALBUQUERQUE; KELNER, 2019; ALBUQUERQUE; KELNER; HUNG, 2019; ALBUQUERQUE et al., 2020; WHELER et al., 2020; WHELER et al., 2021)

6 EVALUATION

This chapter presents key results of stakeholders' evaluation from 2016—2021 regarding the **Toy User Interface (ToyUI) Toolkit's** demonstration and usage evaluation by analyzing creators' working materials and qualitative feedback. Discussions provide critical analysis of tools' usage through the three Human-Centered Design (HCD) stages: inspiration, ideation, and implementation. Two separate sections discuss contributions to hardware–software implementation and data security and compare stakeholders' challenges in face-to-face meetings and remote sessions.

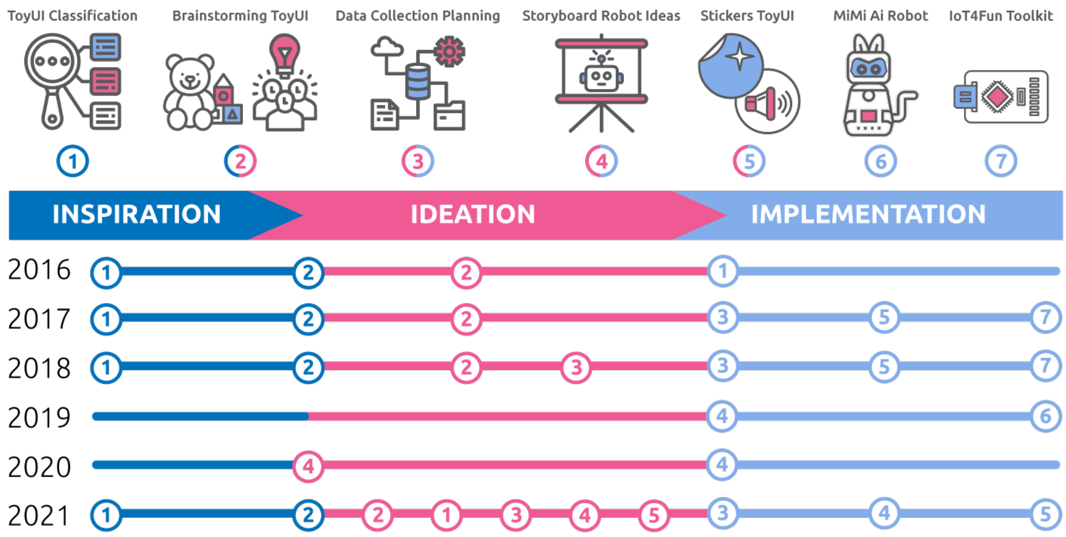
6.1 STAKEHOLDERS' EVALUATION

Referring to **Chapter 4**, this thesis uses demonstration and usage evaluation strategies to assess the ToyUI Toolkit with stakeholders (LEDO et al., 2018). Figure 18 details the stakeholder's evaluation timeline and what HCD tools they included. In Figure 19, stakeholders' evaluation included the following Brazilian, Canadian, and German institutions: *Universidade Federal de Pernambuco (UFPE)* Brazil, *Instituto Federal de Educação, Ciência, e Tecnologia de Pernambuco (IFPE)* Brazil, *Porto Digital* (a tech company from Recife, Brazil), *Serviço Nacional de Aprendizagem Comercial de Góias (SENAC-GO)* Brazil, *Ontario Tech University (UOIT)* Canada, the Non-Governmental Organization (NGO) *Chai Lifeline Canada*, and *Augsburg University of Applied Sciences (AUAS)* Germany. Evaluation strategies comprised of usage and demonstration strategies, resulting in nine long-term usage sessions (12–16 weeks), three short-term usage sessions (4–8 hours), and three project demonstrations.

Most usage evaluation sessions occurred in Brazil, and participants initially fill out consent forms, agreeing to participate in this research, including recording the online sessions for data analysis. Usage evaluation with Canadian and German stakeholders focused solely on the Storyboard Robot Ideas. Results analyses focused on extracting qualitative information on the storyboards' contents (e.g., application thematic and system data collection or expected data collection) since we did not collect stakeholders' feedback in Canada and Germany sessions. We did not request institutional approval to collect user information due to the length and time of evaluation. Demonstration evaluations in Canada included a case study with the NGO *Chai Lifeline Canada*, which did not use any post-evaluation survey or collected feedback from end-users for similar reasons. Likewise, another robot demonstration at UOIT involved a group of teenagers as end-users during an open event on campus but not collected user feedback information.

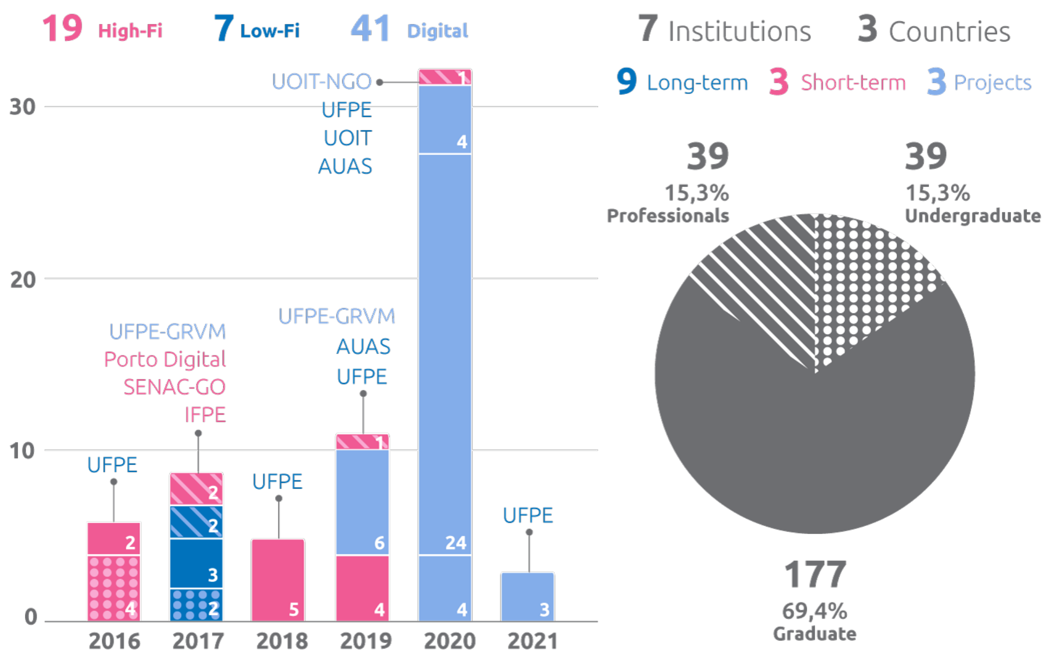
The HCD tools evaluation included 255 stakeholders (i.e., creators) – 177 graduate students, 39 undergraduate students, and 39 professionals. Creators' backgrounds varied

Figure 18 – 2016—2021 treatment evaluation according to HCD stages and tools.



Source: Author.

Figure 19 – Overview of stakeholders' evaluation.



Source: Author.

from Computer Science to Computer, Mechanical, Electric, and Electronic Engineering, Design, Business, and Information Technology (IT). Combined, they implemented 67 ideas, among seven low-fidelity prototypes, 19 high-fidelity prototypes, and 41 digital prototypes. High-fidelity prototypes combine different implementation strategies, including seven prototypes using the IoT4Fun Toolkit (V1–V2) and six prototypes integrating companion robots (i.e., *NAO V5, TIAGo*, and *Zenbo*). Low-fidelity prototypes are paper prototypes' results from the short workshop sessions, and all digital prototypes using the

Zenbo Lab tool are compatible with *Zenbo Junior* robot. Demonstration evaluations include collaboration with the Virtual Reality and Multimedia Research Group (GRVM) researchers (e.g., collaboration to design proof of concept prototypes using the IoT4Fun Toolkits), UOIT researchers (e.g., proof of concept prototypes using Zenbo and Zenbo Jr. robots), NGO *Chai Lifeline Canada* (e.g., collecting user requirements and reviewing the narrative contents), and a participatory design class with UFPE students (e.g., implementing the first version of the MiMi AI Robot app).

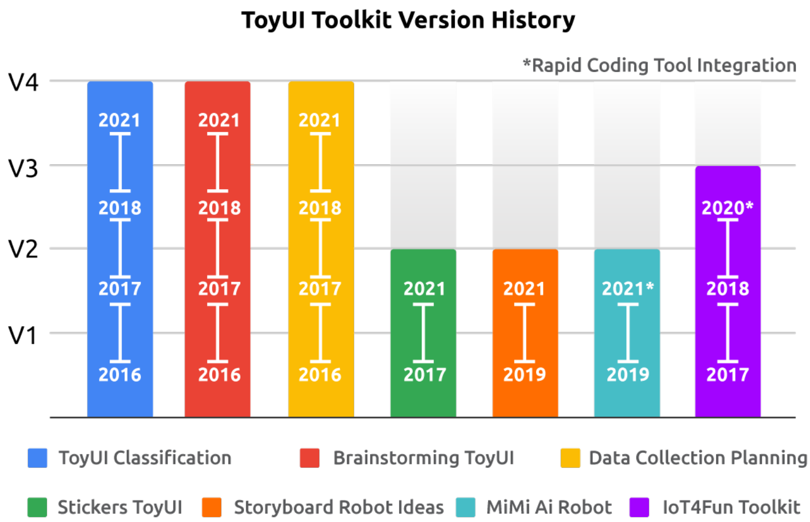
Although conducting long-term evaluation is time-consuming and demands consistency and availability of the participants. Conducting short-term evaluations, such as during events and workshops, may limit the scope of results to a single design cycle or prototype. The reasons this thesis focused on evaluation in a post-secondary educational setting instead of applying them with professionals in the Child-Computer Interaction (CCI) industries are several. First, conducting long-term research in the CCI industries requires cooperation from the companies, which may be affected by economic interests and intellectual property issues. Still, efforts to bridge the gap between academia and industry are necessary, and plans to assess the HCD tools with CCI industries' professionals are part of future works.

Once higher educational intuitions are also stakeholders in the problem context, training the students' User Experience (UX) and IT skills can become a promising strategy for training human resources for the CCI industries. An educational setting permits us to develop a entire project-based learning program and evaluate the HCD tools combined with student assessment (MOURSUND, 1999). Besides, evaluating the learning program with graduate students can favor interdisciplinarity since graduate programs may include students from distinct backgrounds. In contrast, undergraduate programs focus mainly on a single group of stakeholders (e.g., Electronic Engineering or Design students). Note that when we applied the HCD tools with undergraduate and graduate students concomitantly, we did not observe any difference in the prototype's regarding quality or complexity, or any significant challenges when using the HCD tools.

6.1.1 Version History

Figure 20 shows the ToyUI Toolkit's version history. The 2016 preliminary evaluation introduced the original versions of the classification, brainstorming, and data management tools (ALBUQUERQUE; BREYER; KELNER, 2017; ALBUQUERQUE, 2017). The 2017 workshops implemented the low-fidelity prototyping tool (Stickers ToyUI) while developing the first version of the IoT4Fun Toolkit (ALBUQUERQUE; KELNER, 2019). The 2018 session evaluated the updated versions of all existing HCD tools, starring the second version of the rapid prototyping toolkit (ALBUQUERQUE; KELNER; HUNG, 2019; ALBUQUERQUE et al., 2020; WHELER et al., 2020). From 2019 to 2020, we implemented the novel HCD tools to add companion robot components in the ideation and implementation stages – the Storyboard Robot Ideas and MiMi AI Robot. In early 2021, we adapted the following HCD tools to remote training: ToyUI Classification, Brainstorming ToyUI, Data Collection Planning, Stickers ToyUI, and Storyboard Robot Ideas (WHELER et al., 2021). Figures 21 to 23 compare paper-based and digital versions of the ToyUI Classification, Brainstorming ToyUI, and Data Collection Planning tools. Figure 24 shows how the Storyboard Robot Ideas integrates the digital Stickers ToyUI. All digital versions accompany a slide presentation with detailed instructions, which are available online for the CCI community [1]. Due to COVID-19 pandemic restrictions, this thesis does not include evaluating the new IoT4Fun Toolkit (V3) and the Rapid Coding Tool (RCT) integrated with the MiMi AI Robot (V2). Although we developed a prototype of the RCT app, we could not perform the necessary integration tests supporting all hardware functionalities and integration. Testing required working with materials available only in the research facilities at UFPE. Similar to other institutions, UFPE moved all academic activities to remote settings since early 2020.

Figure 20 – Version history of the ToyUI Toolkit.



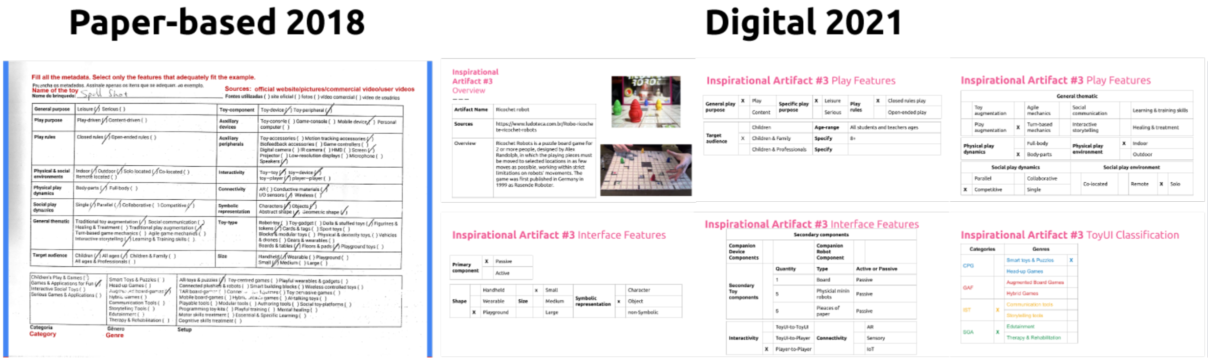
Source: Author.

6.1.2 Prototypes' Highlights

Figure 25 introduces remarkable prototypes distributed into the four categories: Children's Play & Games (CPG), Games & Applications for Fun (GAF), Interactive Social Toys (IST), and Serious Games & Applications (SGA). CPG prototypes reassemble traditional toy and play features by using technology to enhance CCI experiences. Prototypes include toy components, such as a shuttlecock and a plush toy, and simulate games like *hot potato* and *tag*. The GAF prototypes mix physical and digital components and offer more closed-play rules, such as board games, card games, and agile game mechanics. Meanwhile, IST

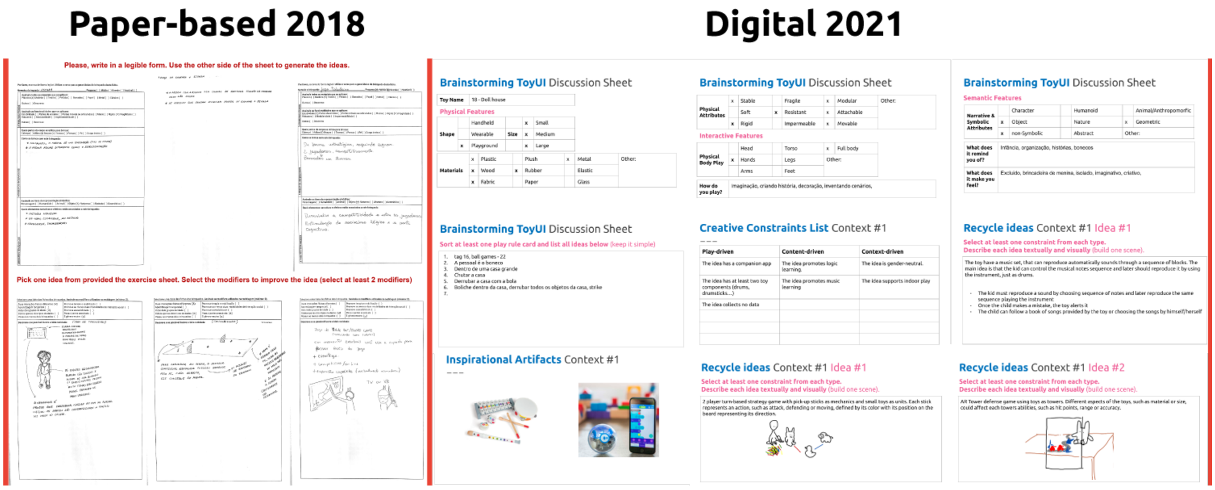
[1] http://www.iot4fun.com/

Figure 21 – Evidence comparison of paper-based and digital ToyUI Classification tool filled by stakeholders.



Source: Author.

Figure 22 – Evidence comparison of paper-based and digital Brainstorming ToyUI resources filled by stakeholders.

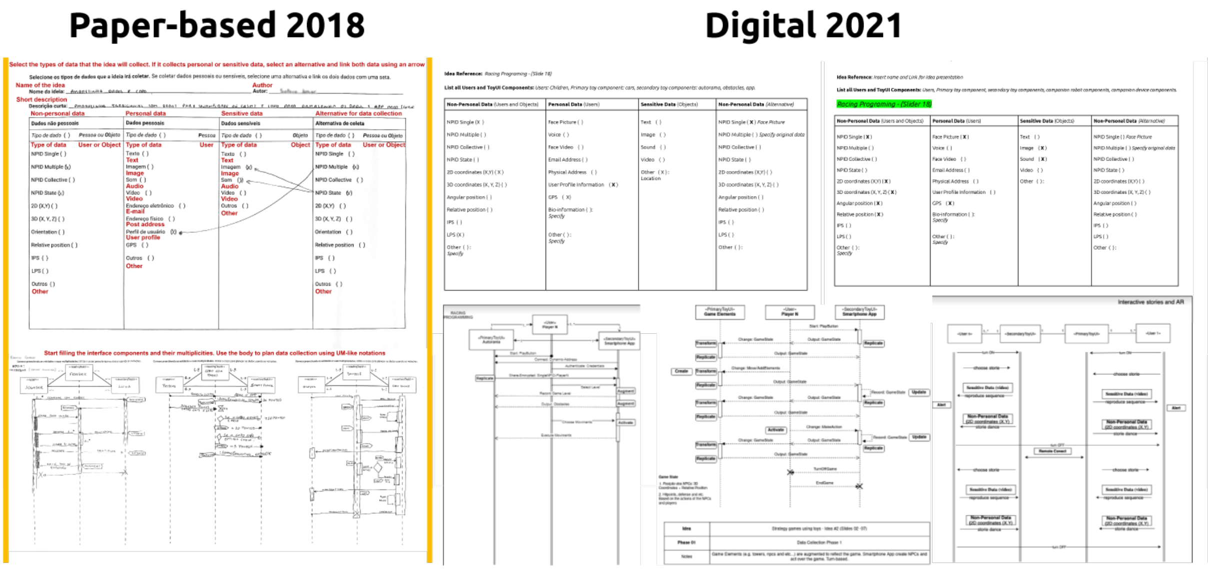


Source: Author.

and SGA prototypes explore Human-Robot Interaction (HRI) features by introducing companion robot components as play mediators or active social actors. Table 31 compares some developed prototypes, classifying them by ToyUI setup and detailing data collection strategies. The non-Personal Data (PD) collection was fully adopted in the prototypes using the IoT4Fun Toolkit. At the same time, custom implementation strategies and HRI tasks included sensitive data collection (e.g., multimedia data) or PD (e.g., voice).

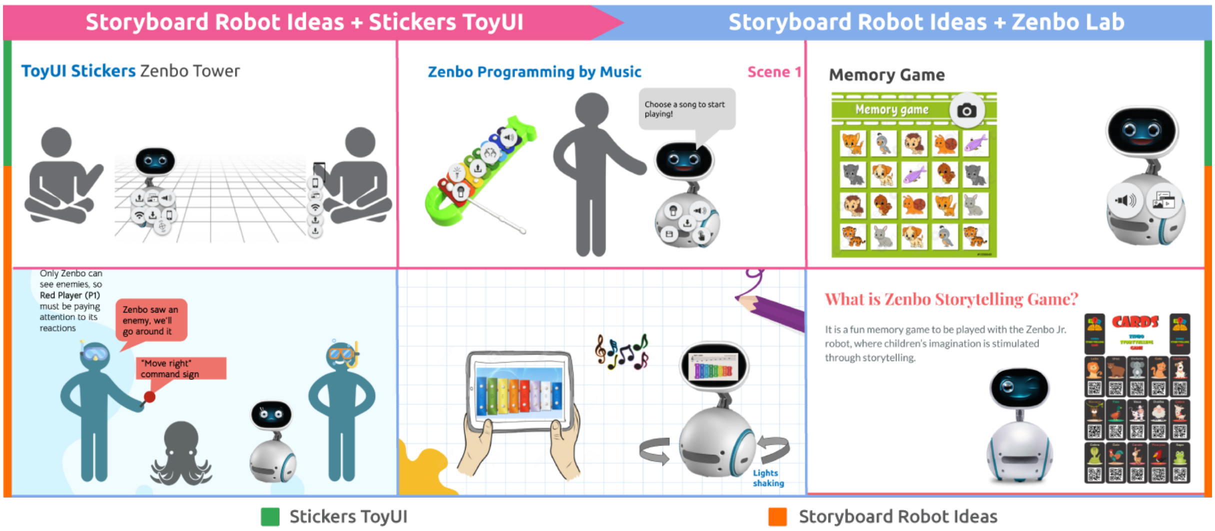
Referring to Table 31, the 2016 prototypes used various implementation strategies that required sensitive data collection, such as using multimedia input to detect Augmented Reality (AR) makers or markerless detection techniques like color and other feature descriptors (e.g., *Cubica*). Alternatives such as using conductive materials and Near-Field Communication (NFC) tags permitted the ToyUI setups to focus on non-PD collection (e.g., *Legends of the World*). The prototype *BUD Monster* using *Microsoft's Kinect* camera supported the user's motion tracking without capturing personally identifiable features (ALBUQUERQUE; BREYER; KELNER, 2017; ALBUQUERQUE, 2017). The 2016's creators

Figure 23 – Evidence comparison of paper-based and digital Data Collection Planning tools filled by stakeholders.



Source: Author.

Figure 24 – Comparison of initial Storyboard Robot Ideas integrating the Stickers ToyUI and final storyboard versions during user assessment.



Source: Author.

faced numerous technical challenges to implementing custom prototypes, impacting in their final results. Many multiplayer ideas ended up as single-player solutions. The main reasons included creators dealing with implementation challenges such as implementing computer vision algorithms robust enough to perform in different indoor and outdoor environments. Other hardware–software integration challenges emerged when connecting hardware components and companion devices using game engine software *Unity 3D* (Unity Technologies, 2021) and *Unreal Engine* (Epic Games, 2021).

In 2017, this thesis developed the first version of the IoT4Fun Toolkit aiming to facili-

Figure 25 – Highlights of the stakeholder's prototypes distributed by ToyUI categories.

Source: Author.

tate hardware–software integration in high-fidelity implementation. We develop proof-of-concept designs with GRVM researchers to assess the toolkit's usefulness (ALBUQUERQUE; KELNER, 2019). The *Smartminton* is a shuttlecock prototype that supports reading NFC tags embedded in the users' gloves. We 3D-printed the toy component using *NinjaFlex* material to support physical collisions. However, the all-in-one Printed Circuit Board (PCB) strategy proved inadequate to fit different physical embodiment, and in 2018 we implemented modularity features in the IoT4Fun Toolkit (ALBUQUERQUE et al., 2020; WHELER et al., 2020). We evaluated the toolkit robustness by testing it with graduate students at UFPE. Students implemented five ToyUI setups incorporating different IoT4Fun Toolkit modules and evaluate them with users in playtesting sessions (ALBUQUERQUE; KELNER; HUNG, 2019). For instance, the *Hulahoop Hero* embeds the toolkit in a plastic tube embodiment, challenging the toolkit's adaptability features. All prototypes focused on the non-PD collection strategy mixing NPID, UPS, and motion tracking information. Prototypes like *Cube Music* and *Hulahoop Hero* use Bluetooth connection to integrate a

Table 31 – ToyUI setups' highlights and adopted data collection strategies: PD, non-PD, and sensitive data (SD).

Prototype	**ToyUI setup**	**Year**	**Data Collection**
Cubica	Connected toy figurines	2016	SD (multimedia: color tracking)
BUD Monster	Hybrid arcade games	2016	non-PD (Non-Personal Identification (NPID) and Unidentifiable Positioning System (UPS))
Legends of the World	Connected toy figurines	2016	non-PD (NPID and UPS)
Smartminton	Toy-centered games	2017	non-PD (NPID)
Cube Music	Connected toy figurines	2018	non-PD (NPID and UPS)
Hulahoop Hero	Hybrid arcade games	2018	non-PD (NPID and motion tracking)
Zombie-tag	Playful wearable and gadgets	2018	non-PD (NPID)
Guitar Tuner	Playful training	2019	SD (multimedia: sound/music)
Karate NAO	Playful training	2019	SD (multimedia: fiducial marker)
Kindergarten Zenbo	Essential and specific learning	2019	non-PD (NPID)
Treasure Hunter	AI-talking toys	2019	SD (multimedia: feature detection)
A Cookie Story	Playable tools	2020	SD (multimedia: color tracking)
Zenbo Zoo	Cognitive skills treatment	2020	non-PD (NPID)
Zenbo Roulette	Essential and specific learning	2020	non-PD (NPID) and PD (voice)
My friend Bo	Mental healing	2020	PD (name, pictures, and voice)
Zenbo Recycling	Essential and specific learning	2020	non-PD (NPID) and PD (voice)
Zenbo COVID-19 Companion	Mental healing	2020	non-PD (NPID) and PD (voice)
Zenbo Explorer	Playable tools	2021	SD (multimedia: color tracking) and non-PD (UPS)
Zenbo Memory Game	Modular tools	2021	SD (multimedia: fiducial markers)

Source: Author.

secondary companion device to display content and regulate play rules. Prototypes like the smart glove *Zombie-tag* uses NFC to integrate secondary toy components (bracelets and playing cards), supporting screenless and full-body interactions.

In 2019, we started to introduce HCD tools to include companion robot components in the ToyUI setups. The goal was to introduce Artificial Intelligence (AI) features in the prototypes since the IoT4Fun Toolkit solely focuses on non-PD collection types (i.e., motion tracking, UPS, and NPID). Implemented HRI ideas are expected to collect more sensitive data and PD, such as voice and other multimedia data. We stimulated creators to search for alternative inputs to the HRI tasks to overcome voice-based interaction, particularly the Brazilian students, since there are limited Portuguese language resources. For example, *Karate NAO* and *Guitar Tuner* applications use a companion device to organize and display contents to the robot using fiducial markers (sensitive data). *Karate NAO* uses the companion device to request the training positions, and *Guitar Tuner* to select music partiture. *Guitar Tuner* also includes a physical guitar as a ToyUI component, in which the child would learn how to tune the guitar note by note and get feedback from the robot on the overall score after playing a song. The creators find it challenging to use the robot's embedded microphone to detect the guitar sound. They proposed a technical advancement in filtering the sounds using a novel algorithm; their efforts are published in (MELO et al., 2020). The UFPE classes co-occurred with AUAS classes using the *Zenbo* robot. We mixed ideation resources to evaluate similar design concepts using different robot embodiment. For instance, the robot application *Kindergarten Zenbo* that supports teachers as an active social actor, monitoring and entertaining kids at school, also has versions using the *NAO V5* and *TIAGo* robots.

In a participatory design class, we implemented the first version of MiMi AI Robot application and robot embodiment, aiming to support more editing freedom using open-source HRI resources. As a preliminary result of collaborative efforts with graduate students, we implemented the *Treasure Hunter* game using the MiMi AI Robot paired with a secondary companion device. The game uses all available resources of MiMi's robot embodiment and AI application, such as the motors and Light-Emitting Diode (LED)s, and implements machine learning models for object detection and the dialogue system. In the proof-of-concept game, MiMi requests the companion device to find a treasure in the room (e.g., a teddy bear, a keyboard, or a mug). Then, the child searches for the toys and objects to show them to MiMi's embedded smartphone camera. The MiMi can say the name of the object in the Portuguese language to teach words to the child (e.g., MiMi says "we call it *ursinho*" to the teddy bear interaction). More evaluation sessions are necessary to further state MiMi AI Robot applicability and technical limitations to develop different ToyUI setups.

In 2020, we further explored the idea of integrating ToyUI setups with companion robot components due to the potential benefits of using the physical toy components as alternative inputs to voice-based interaction, reducing the need for sensitive data and PD collection. In January 2020, we developed a storytelling tool using the robot *Zenbo* and colorful pads as the input for the HRI tasks as a proof-of-concept design. We tested the implementation in a Wizard of Oz (WoZ) evaluation with two children from the NGO *Chai Lifeline Canada*. This project aimed to use companion robots to support home education for children who are prevented from attending regular school activities due to severe or chronic illness treatments (e.g., cancer and cystic fibrosis). We developed an interactive storytelling animation named *A Cookie Story* to provide companionship and teach math lessons for grade 5 students (i.e., fraction units). This playable tool included a series of integrated CCI experiences, such as clapping hands to break the eggshell, hide from the characters by covering the face, and replying to the cookie recipe questions using the colorful pads. The presence of these ToyUI components permitted us to playtest the robot application with two siblings (a boy aged six and a girl aged seven) at the same time. The pads gave them the means to compare their visual responses, which generated spontaneously and humorous CCI, mostly when they disagreed on their responses. The integrated ToyUI setup reserved the children's undivided attention for 16 minutes of the demonstration session. Unfortunately, the COVID-19 pandemic has delayed testing the new generation of IoT4Fun Toolkits integrated with the companion robot *Zenbo Junior*, limiting research data on integrating toy components and companion robot components.

During the pandemic, we moved research efforts to remote training. Initially, we used the Storyboard Robot Ideas combined with the *Zenbo Lab* tool to support creators in digital prototypes. Several prototypes addressed the COVID-19 social isolation context, such as developing edutainment tools to support homeschooling activities (e.g., *Zenbo Roulette* and *Zenbo Recycling*), and providing companionship to children (e.g., *My Friend Bo* and *Zenbo COVID-19 Companion*) (LOADES et al., 2020). More inclusive designs target at neurodivergent children like the *Zenbo Zoo* supporting design guidelines for autistic children (DICKSTEIN-FISCHER et al., 2018). However, none of the 2020 digital prototypes included a user evaluation assessment. Challenges of performing remote user evaluation sessions include limited or no access to physical robots and resources and the lack of the robots' physical presence when demonstrating HRI tasks remotely). We continuously invited UX and IT professionals to provide qualitative feedback during ideas development in the remote classes, including inviting HRI researchers and professionals from the robot industry to speak about HRI topics during the AUAS and UOIT classes (e.g., *Misty Robotics, Catalia Health, Hanson Robotics* and *SoftBank Robotics*). In early 2021, we evaluated the digital versions of the HCD tools supporting a comprehensive evaluation on remote training, including remote user assessment with children–parents pairs (WHELER et al., 2021). Digital prototypes like the *Zenbo Memory Game* and *Zenbo Explorer* expected to integrate physical toy components as input resources and the companion robot component as a social play regulator and as a co-player, respectively.

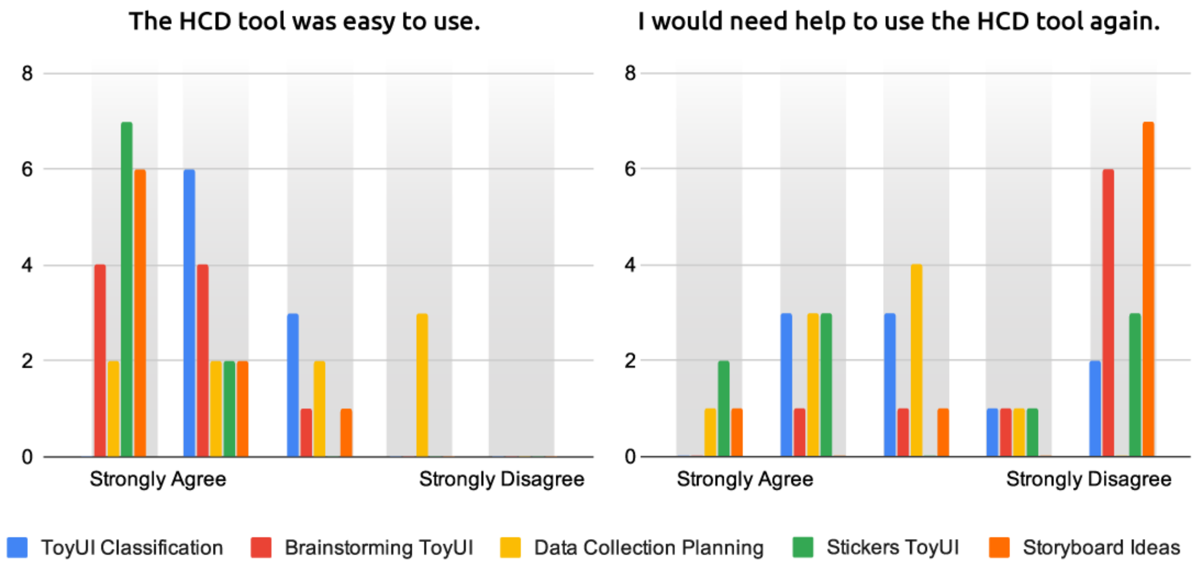
6.2 HUMAN-CENTERED DESIGN EVALUATION

Over the evaluation years, we introduced the ToyUI Toolkit in different HCD stages, supporting us to improve each tool and generate new versions. In the 2021 UFPE session, we used an A/B evaluation strategy as described in the research methods (refer to **Chapter 4**) to evaluate the digital versions of the ToyUI Toolkit (LEDO et al., 2018). Between November to December 2020, nine male graduate students (25–35 age range) developed three ToyUI projects, following the HCD cycle without the ToyUI Toolkit's assistance.

Then, between January to March 2021, they used the HCD tools weekly when developing three new ToyUI projects in different teams. This evaluation aimed to assess if the HCD tools are easy to use, clear to understand and adequately distributed in the HCD stages.

Figures 26 and 27 compare results from the online survey on the HCD tools used during remote training. Overall, results suggest that the digital tools are easy to use, do not necessarily require assistance to use, and are adequately distributed in the HCD stages. Some issues emerged in the tools individually, such as requiring more time to use them during evaluation, improvements in the instructional materials, and personal assistance during the first usage. The tools that performed better are the Brainstorming ToyUI, Storyboard Robot Ideas, and Stickers ToyUI. The ToyUI Classification and Data Collection Planning required more training time to support their benefits fully. The following subsections discuss the ToyUI toolkit usage and adequacy during the three HCD stages, considering information from the remote training survey and qualitative assessment of the ToyUI Toolkit's version history.

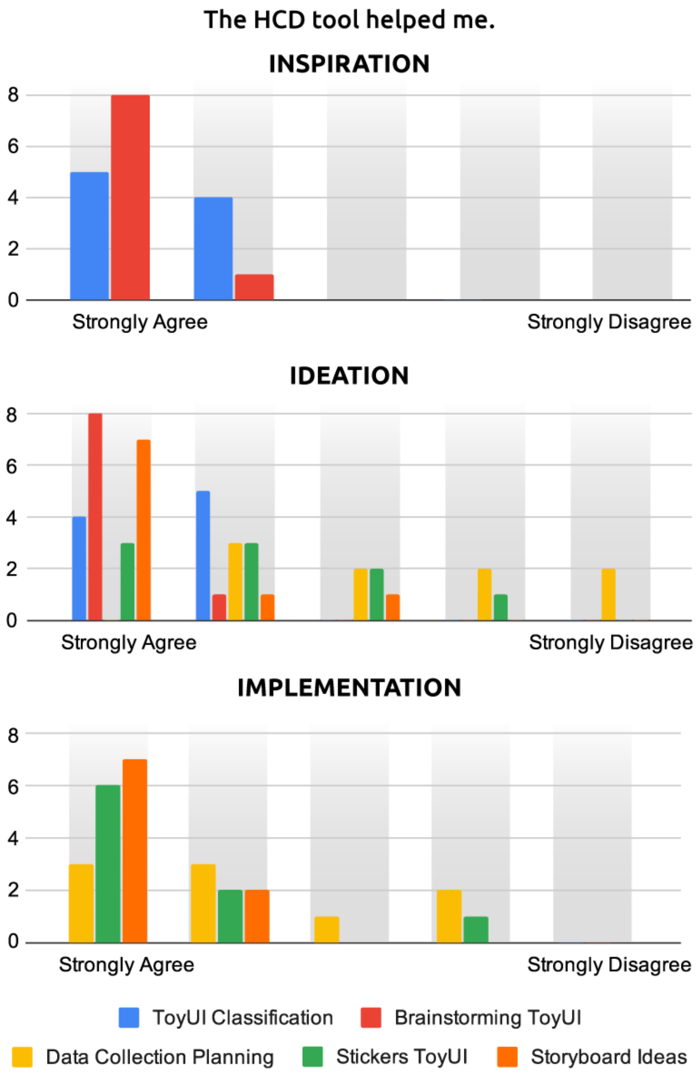
Figure 26 – 2021 evaluation results of the HCD tools during remote training.



Source: Author.

The post-evaluation survey also gathered students' feedback on HCD stages challenges after each project. Regardless of the ToyUI toolkit usage, they faced practical challenges during all three HCD stages. Inspiration challenges in the first project included difficulty seeking inspiration and design contexts involving children, described as *"startup the creative engine"* and difficulty to *"generate innovative ideas"* for CCI. After the second project, students mentioned issues in seeking a second context for their projects and combining physical and social play in the ToyUI setups. Some wish they would have more time to improve the initial projects, but using the HCD tools, as stated in *"maintaining only the first project during the course, but using the methodology and tools of the second project. The main idea is to have more time to work on each deliverable, better under-*

Figure 27 – 2021 evaluation results of the tools according to HCD stages.



Source: Author.

standing, obtaining more feedbacks, and delivering a complete project at the end." Ideation challenges in the first project were related to generating ideas in general, generating ideas before defining technological aspects, and incorporating user feedback in idea generation. In contrast, the ideation challenges from the second project related to the high volume of ideas and the many steps introduced by the HCD tools.

Implementation challenges in the first project are mainly related to user evaluation issues and the lack of the physical robot embodiment for technical implementation. User evaluation issues were reduced in the second project when evaluating the ideas with the same user sample and using the Storyboard Robot Ideas as a supporting resource. However, the lack of physical robot embodiment remained an issue for all creators in the implementation stage. Common issues in both projects are related to students' teamwork, availability, time management, and the lack of face-to-face social interaction. Students enjoyed the in-class activities and interaction with UX and IT professionals. However, they complained about the high volume of reading materials (in the first project) and high volume of practical activities (in the second project), wishing that activities were better distributed along the 16-weeks. A further evaluation using the HCD tools since the first classes can balance theoretical and practical activities. The following subsections provide a critical discussion of the ToyUI Toolkit, including information from this online survey. Discussion compares digital and paper-based tools from previous evaluations, using the strategies described in **Chapter 4** to perform a summative content analysis of working materials in each HCD tool.

6.2.1 Inspiration Tools

The 2016's interviews suggested that the ToyUI Classification tool can play a significant role in communicating the ToyUI topic to the creators in the inspiration stage. Particularly when they have little or non-experience with integrated CCI applications (ALBUQUERQUE; BREYER; KELNER, 2017; ALBUQUERQUE, 2017), the first version of this tool consisted of a relational model that also included data management information. According to interviewees, the tool also helped them planning overall aspects of the ToyUI setup and comparing setups before and after the implementation stage. For example, interviewees' comments included that the tool *"helps to define the setup"* and aided their team *"in defining the system requirements before implementing the play functions"*.

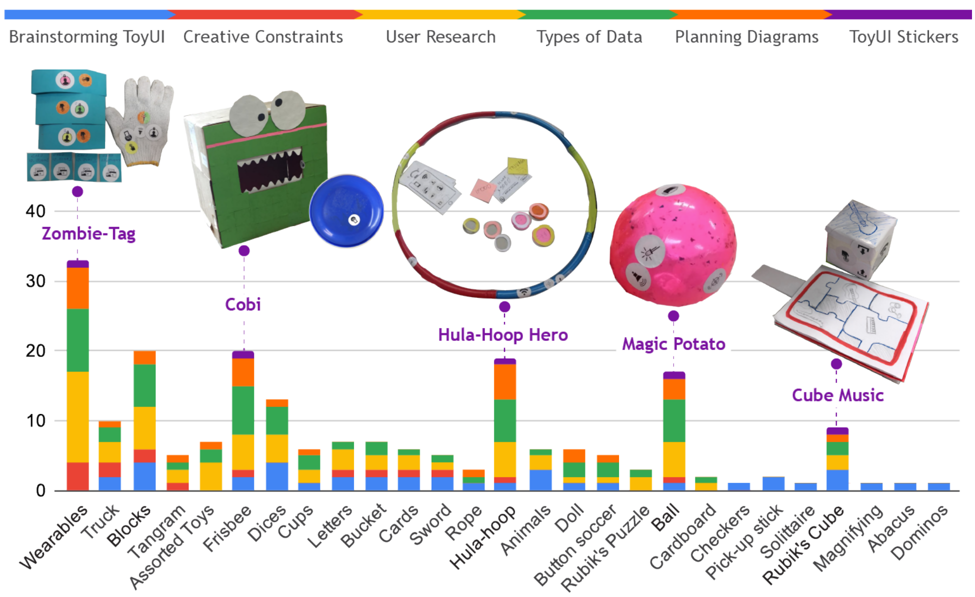
This tool's current version aims to support a clear understanding of the ToyUI setup features while facilitating inspirational artifacts analysis. In the 2021 online survey, all creators expressed positive comments on the classification tool's usefulness. They either agreed or strongly agreed that it helps in the inspiration stage, refer to Figure 27. A creator mentioned that *"a tool that classifies the immense diversity of ToyUI can be interesting in the construction of new projects"* and other *"I found it very complete in describing the interfaces."* However, some creators also expressed that they needed more training to improve understanding the ToyUI features. They noticed that many artifacts would mix or overlap features from different categories and genres, confusing them.

6.2.2 Ideation Tools

Over the years, we performed significant changes in the Brainstorming ToyUI tool. In 2017, we decided to predefine a set of physical toys for the ideation sessions. Initially, we requested creators to bring their toys for the ideation sessions. However, they would often get attached to affective and semantic aspects, such as character design and narrative aspects, which gave biases to their concepts and made it challenging to polish them during the implementation stage. For example, the *Legends of the World* prototype was inspired by the *Pokemon* series, which became an issue in the first versions of the prototype since they limited the set of play rules to the classic single battle mode. During the user evaluation sessions following the HCD flow, including sessions with end-users and specialists, the team implemented a new game dynamics by moving the play tokens on the screen in three possible positions (i.e., attack, defense, and neutral). We also decided to implement the structured ideation sheets to guide them during the sessions (refer to Figure 22).

Structured materials facilitate performing summative content analysis of the ideation stages. In Figure 28, the summative content analysis shows the types of toys from the early ideation to the first stage of implementation in the 2018 session. The keywords graph demonstrates how ideas evolved from the Brainstorming ToyUI session until selection in the low-fidelity prototyping practice using the Stickers ToyUI. The graph shows that four of five selected ideas came from the first ideation session, one appeared after the creative constraints practice, and that ideas kept emerging after user research practices. In the 2021 version, the Brainstorming ToyUI incorporates more user research information in the creative constraints stage. The creative constraints practice was first introduced in 2018, aiming to recycle and improve the brainstorming ideas. In the current version, the Brainstorming ToyUI introduces a more explicit link with the ToyUI Classification tool by supporting inserting inspirational artifacts related to the context of use in the ideation process.

Figure 28 – Summative content analysis of 2018 session counting the types of toys from ideation to implementation.



Source: Author.

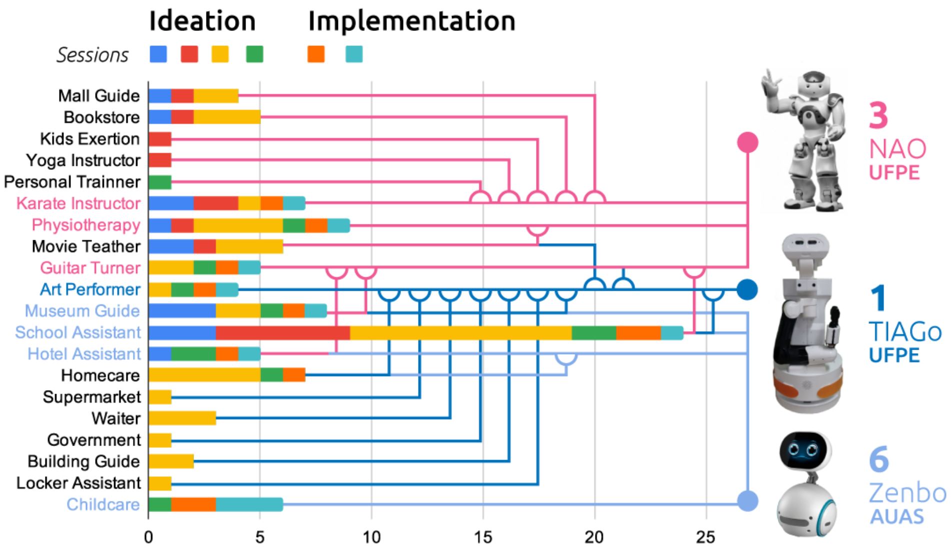
In 2018, we introduced the Data Collection Planning tool as a mandatory step to the idea selection instead of the 3-choice voting system that we used before. However, results from the 2021 survey suggest that the data planning diagrams may be overly complex to be introduced in the early ideation stage, requiring additional training so that all creators can assimilate the non-PD patterns and concepts. The first step of data planning occurred without significant issues, but the data planning diagrams require more idea details, such defining ToyUI setup components and play rules. The Data Collection Planning tool received better evaluations when applied to the implementation stage, refer to Figure 27. Despite the many iterations and improvements made in the data planning tool, creators often find this tool complex and require more time to understand and use its benefits. The Unified Modeling Language (UML)-like notations were introduced to this tool, aiming to benefit from previous experiences creators might have with visual modeling languages.

A creator said it was *"a little complex at first, but it served to align the product flow."* Another claimed that *"it facilitates identifying points for improvement in data usage planning, but in my view, this was not only due to the tool, but rather, combined with the other dynamics we worked on"* (the other HCD tools). For one creator, the data planning tool gave him *"security"* to define the project scope, and he would use it again in future research and market solutions. However, a few creators *"felt lost"* and *"confused"* when using this tool. Three of them suggested that they needed more time to assimilate concepts and that it took them several practices to learn how to use the diagram. Suggestions included improving the instructional materials for remote training, such as making video tutorials and providing more examples to build the diagrams. Comparing with the experience and feedback we had in the 2018 case study (ALBUQUERQUE; KELNER; HUNG, 2019), the 2021 students seemed to lack the benefits of real-time support with the instructors. They used the diagrams as part of homework in the remote training, suggesting that the initial practices are more suitable in face-to-face meetings and monitored in-class sessions.

Figure 29 presents the Robot Ideas Storyboards' content analysis relating to three available robot embodiment's from UFPE and AUAS case studies. UFPE and AUAS classes co-occurred, so we introduced the *NAO V5* robot template to UFPE students first. Then, UFPE students used the *TIAGo* template to recycle *NAO V5* robot ideas and generate new ones. Later, we provided AUAS students with UFPE's *NAO V5* and *TIAGo* robot ideas before using the *Zenbo* template in their ideation sessions. As a result, many ideas overlapped and evolved when adapted to different robot embodiment. These results consist of an experimental ideation dynamic we performed by mixing UFPE and AUAS work materials. The goal was to induce creators to modify similar ideas based on different robot embodiment features, which demonstrated interesting in generating a higher volume of ideas and recycling concepts in different HCD stages since some ideas were exchanged even after initial prototyping.

During the 2020 pandemic, the storyboards became essential to generate and communicate ideas to the online classes. For instance, the students used the storyboards during assessment meetings to discuss their implementation journey with the class. According to the 2021 evaluation, refer to Figures 26 and 27, most creators strongly agree that storyboards are easy to use, do not require extensive training, and are helpful in both ideation and implementation stages. Among their comments, we highlight some: *"it made it possi-*

Figure 29 – Summative content analysis of 2019 storyboard templates counting the number of thematic ideas from ideation to implementation.



Source: Author.

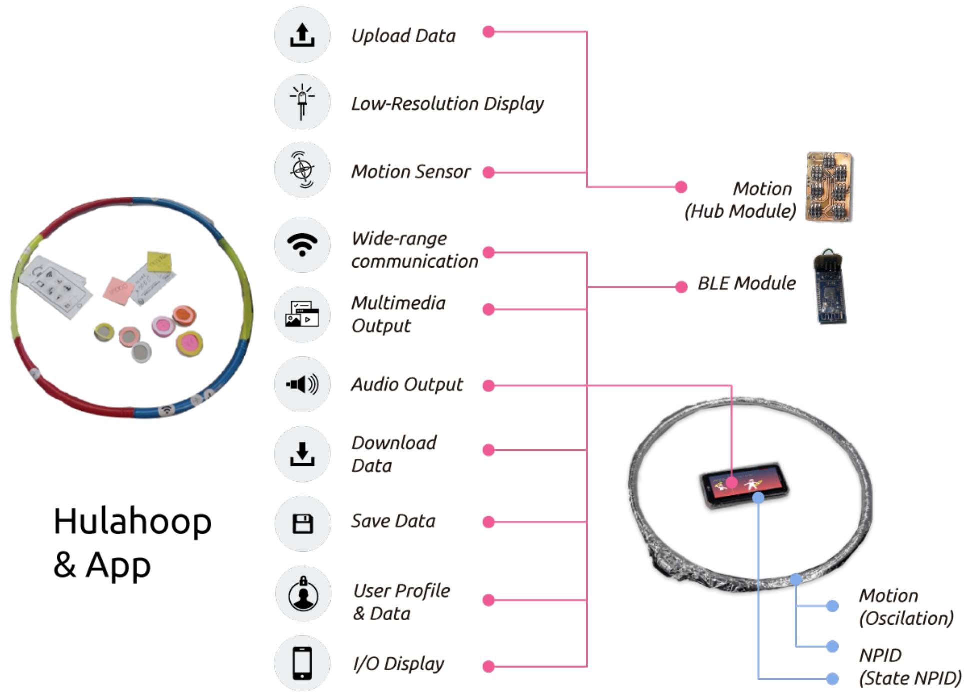
ble to define the HRI tasks scope better," "it was of fundamental importance, contributed to the definition of the interactions between robot and child, and the final prototyping", and *"practical, it helped a lot in describing and creating the ideas."* Creators also associated its usefulness to collect user feedback from children and parents during the pandemic, *"it became much easier to present our ideas to parents and children"* and *"it was very useful to explain the game rules to new users."* User assessment tools are further discussed in a separate subsection.

6.2.3 Implementation Tools

Figures 30–34 compare low and high-fidelity prototypes showing content analysis of the Stickers ToyUI and IoT4Fun Tookit modules. The connections in pink link planned with implemented setup decisions and blue connections detail adopted non-PD collection strategies. The Stickers ToyUI selected in the 2018 low-fidelity prototypes and the number and nature of planned ToyUI components remained essentially the same during implementation. In most cases, the translation of selected stickers and toolkit modules are straightforward (e.g., *Magic Potato, Cobi,* and *Zombie-Tag*). The selected Stickers ToyUI also relates to data planning decisions in *Zombie-Tag, Hulahoop Hero* and *Cube Music* (e.g., data storage behaviors and inputs/outputs of companion applications). In some situations, implementation challenges and opportunities interfere with initial setup decisions. For instance, the *Hulahoop Hero* did not implement the visual module in the toy component due to limitations of its physical constraints. *Cube Music* opted to use a complex input strategy instead of the single input (they expected to use buttons at first), using UPS data to select the cubes' faces. Two prototypes adapted the IoT4Fun

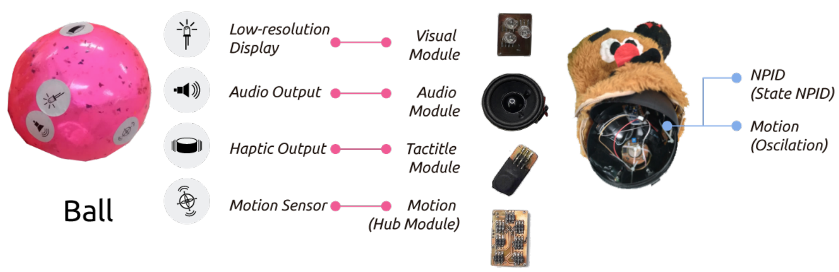
Toolkit V2. The *Magic Potato* modified the battery module to use more current and the *Zombie-tag* replaced the auditory module with a buzzer to reduce its size. These issues were addressed in the IoT4Fun Toolkit V3 (2020), as discussed in **Chapter 5**.

Figure 30 – Hulahoop Hero low and high-fidelity prototypes.



Source: Author.

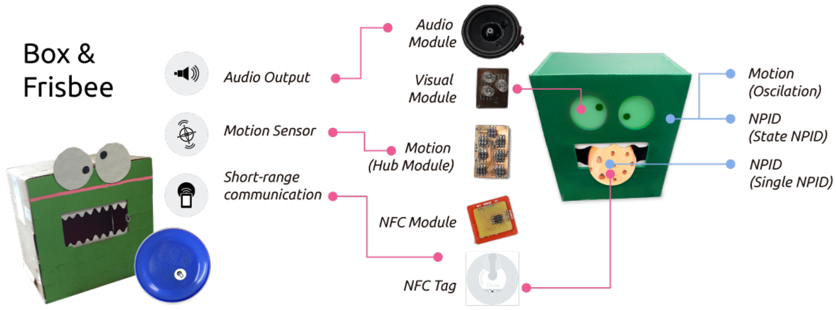
Figure 31 – Magic Potato low and high-fidelity prototypes.



Source: Author.

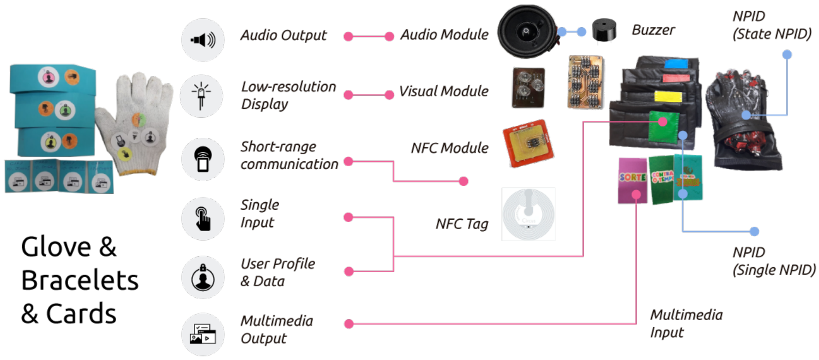
The Stickers ToyUI were first introduced in 2017 workshops and have not changed until their digital versions in 2021, which are now integrated with the Robot Storyboard Ideas practice. They have performed well in supporting in-person low-fidelity prototyping sessions by helping teams define the technology approaches for the ToyUI components. In 2021, most creators strongly agreed that the digital version was easy to use and helpful during the implementation stage. However, similar to the Data Collection Planning tool, some creators felt confused about some stickers' meaning, such as the *complex input'* sticker, and admitted they would need further assistance to use them again. Still, several positive comments included: *"very good, it was easy to communicate the robot interface*

Figure 32 – Cobi low and high-fidelity prototypes.



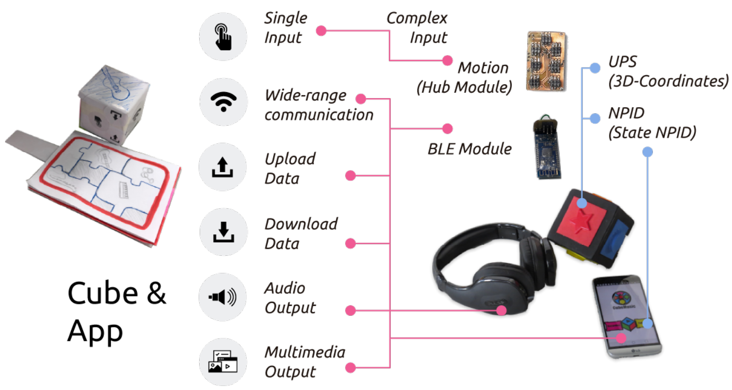
Source: Author.

Figure 33 – Zombie-tag low and high-fidelity prototypes.



Source: Author.

Figure 34 – Cube Music low and high-fidelity prototypes.



Source: Author.

with the stickers", "easy, complete, practical, helped a lot in describing and creating the ideas", "easy to use and intuitive." One creator acknowledged that the *"idea of using stickers to represent inputs and the devices' needs is interesting"* and it is *"a simple and practical way to pass on information."*

The IoT4Fun Toolkit aims to facilitate hardware–software integration challenges while favoring the implementation of non-PD collection strategies. A detailed evaluation of the 2018 version (V2), including a critical review of the initial 2017 prototypes using the single-board version (V1), is available as a scientific contribution (WHELER et al., 2020). Conclusively, the modular PCB strategy is an adequate strategy to embed various toy components, so the hardware modules fully support implementing a non-PD collection strategy for ToyUI setup design. However, issues related to creators' cybersecurity practices kept emerging, along with necessary improvements on miniaturization, robustness, and battery consumption aspects (ALBUQUERQUE et al., 2020). Technical aspects are fully or partially addressed in the 2020 version (V3) as discussed in **Chapter 5**. Unfortunately, due to remote work limitations during the COVID-19 pandemic, this thesis does not include usage or demonstration evaluations with the new IoT4Fun Toolkit (V3). Prototyping and digital fabrication resources are limited during remote work, and face-to-face meetings are suspended at UFPE and the GRVM facilities. The current research data still lacks a more comprehensive stakeholders' evaluation of the new versions of the high-fidelity implementation tools. As we implemented the MiMi AI Robot in a participatory design setting, usage evaluation remains limited to a single case study. Future works discuss opportunities for research continuity and investigation by other CCI researchers. A critical discussion on the identified vulnerabilities in the second version appears in a separate subsection.

6.2.4 User Evaluation Tools

Face-to-face meetings permitted us to include user evaluation sessions in the HCD stages (refer to Figures 35–38). User evaluation occurred with four types of users: UX and IT specialists (i.e., researchers and professionals), adult users (university students), children, and parents. We consistently invited UX and IT specialists to participate in all classes (including remote classes). In 2016 and 2018 evaluations, we organized open playtesting events to support user evaluation with university students. 2016 event included Computer Science and Design students, and the 2018 event invited a group of Physical Education students at UFPE. Stakeholders tested prototypes with children during field research, and user feedback supported them in improving both the play and interface features of their projects. For instance, Figure 37 shows how the *Magic Potato* prototype's appearance evolve through user feedback. Improvements included suggesting changes in the bomb's appearance (that looked like a hat initially) and the character's face (mouth and eyes).

Demonstration sessions with children also include the partnership with the Canadian NGO *Chai Lifeline Canada*. We collaborated with the NGO and UOIT researchers through participatory design practices, developing the IST application, *A Cookie Story*, to interact with a 6-year-old boy recovering from brain surgery and his sister (7-year-old). Several media outlets covered this demonstration session, including a live piece airing on the local news (e.g., *CTV News, CityTV,* and *CBC Toronto*). Another demonstration with a group of teens at UOIT tested a memory game with the robot *Zenbo* and the colorful pads in a WoZ session. Other robot demonstrations occurred at UFPE in 2019, including a live dramatic play using the robot *TIAGo*.

Figure 35 – Photo evidence of face-to-face group sessions during thesis' evaluation.

Source: Author.

Figure 36 – Photo evidence of playtesting sessions during thesis' evaluation.

Source: Author.

During the 2020 sessions, user assessment was limited to invited specialists to provide feedback during ideation to implementation stages. In 2021, we tested user evaluation strategies to evaluate digital prototypes remotely with children–parents pairs using the ToyUI Toolkit resources (i.e., Storyboard Robot Ideas and System Usability Scale (SUS)-Kids). Creators collected feedback with parents and children on two occasions. First, in the initial projects without the HCD tools assistance, then, the second projects used the Robot Storyboard Ideas as a resource. Initial comments about user evaluation challenges

Figure 37 – Magic Potato evolution through user evaluation feedback.

Source: Author.

Figure 38 – Photo evidence of robot demonstrations during thesis' evaluation.

Source: Author.

included finding available volunteers, scheduling user evaluation sessions online, presenting the digital prototypes to collect user feedback, and applying the SUS with children and parents. Creators used a modified version of the SUS questionnaire for testing with children provided by (PUTNAM et al., 2020) and the Emoji-Likert scale that we provided to them.

As stated before in the discussion, the Robot Storyboard Ideas played a crucial role in supporting creators when conducting user research. Although creators faced similar challenges related to scheduling the user feedback sessions, they claimed that the second experience became easier for several reasons. First, they could contact previous volunteers for the second assessment round. Since part of the participants had previously experienced the robot ideas from the first project, creators claimed that they provided more helpful feedback on the second project. They also said that many parents would question robot embodiment features at first, such as *"why the robot does not have arms?"* instead of commenting on the HRI applications and contents. They said that similar questions still arose from first-comers but that the storyboards helped them communicating the projects better.

6.3 DATA SECURITY AND PRIVACY CHALLENGES

A stated research goal is that the HCD tools would support creators in making better data management decisions that prioritize privacy by design principles (CAVOUKIAN; POPA, 2016). However, the strategies to implement the ToyUI setup components, such as selecting hardware components and robot embodiment functions, largely influence those data management decisions. Table 32 details a data security and privacy vulnerability analysis of the IoT4Fun Toolkit (2018 version) based on the threat taxonomy items defined by (SHASHA et al., 2018) and (CARVALHO; ELER, 2017). Table 33 compares students' projects with identified vulnerabilities. The vulnerability analysis aims to assess the impact of data collection planning on the creators' data security practices after the 2018 session. In overview, the vulnerabilities appear to be related to the communication modules selected by stakeholders. The Bluetooth module vulnerabilities include V-3, V-6, and V-7, and we added the V-8 item to the original taxonomy to address specific issues with the NFC module. Encryption vulnerabilities (V-5) are common to both communication protocols. The *Magic Potato* does not offer communication vulnerabilities since it does not implement connectivity features. Vulnerabilities are expected to be overcome using the secure RCT integrated with the 2020 version.

In conclusion, the toolkit by itself can not prevent poor data security practices when creators implement software and hardware integrated behaviors. On top of creators overlooking for aspects related to user authentication and data encryption, they forcibly used static Media Access Control (MAC) addresses for Bluetooth Low Energy (BLE) connection to facilitate quick implementation instead of the recommended dynamic addresses. The RCT app aims to overcome these issues by offering a predefined infrastructure to support reliability aspects, such as data encryption, user authentication, and secure communication channels. A combined effort permeating all HCD stages is necessary to ensure those desirable qualities. The Data Collection Planning tool, Stickers ToyUI, Robot Storyboard Ideas, and the IoT4Fun Toolkit aim to support such decisions when used together. Current research data does not include stakeholders' evaluation of the 2020 version, and evaluation on the RCT app combined with the other HCD tools is subject to future work efforts.

Table 32 – Identified data security and privacy vulnerabilities in the 2018 IoT4Fun toolkit.

VULNERABILITY	DESCRIPTION
V-1. Unauthorized-config-physical	The toolkit configuration can be altered using the USB recorder module without requesting authentication.
V-2. No-local-data-protection	An adversary can retrieve data stored locally in the toy's internal storage or within the mobile app.
V-3. Unauthorized-config-nearby	An attacker can download the mobile app, connect to the toy component, and maliciously configure it.
V-4. Insecure-Bluetooth-practice	Bluetooth communication uses static MAC addresses and pairs without requesting authentication.
V-5. Unencrypted-comm-channels	Information exchange between different parties is unencrypted and can be accessed or modified.
V-6. Denial of Service	More than one device can send commands to the toy component, making it unable to respond adequately.
V-7. Tampering	Modification of the configuration file of the mobile device or modification of information exchanged through network communication between the components.
V-8. Insecure-NFC-practice	Tag information is unencrypted and permits retrieving stored information, including tampering with it or making a malicious configuration, such as limiting further readings.

Source: (SHASHA et al., 2018; CARVALHO; ELER, 2017; ALBUQUERQUE; KELNER, 2019).

Table 33 – Identified vulnerabilities in each students' prototype

PROTOTYPE	V-1	V-2	V-3	V-4	V-5	V-6	V-7	V-8
Magic Potato	X	X	–	–	–	–	–	–
Cobi	X	X	–	–	X	–	–	X
Zombie-Tag	X	X	–	–	X	–	–	X
Hulahoop Hero	X	X	–	X	X	X	X	–
Cube Music	X	X	–	X	X	X	X	–

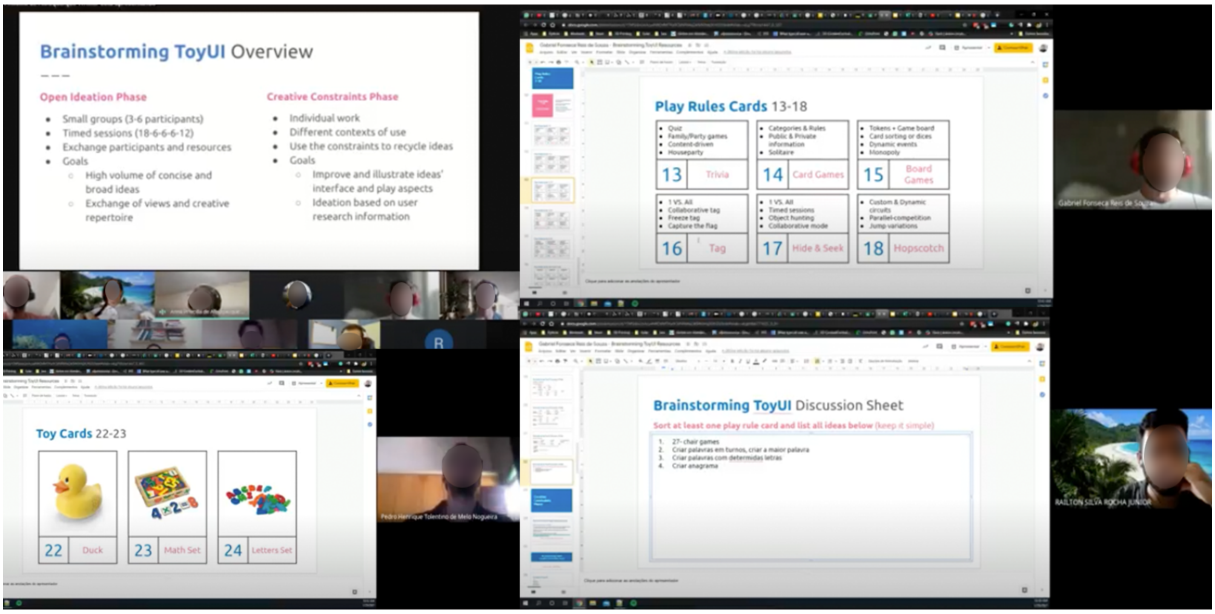
Source: Author.

6.4 REMOTE TRAINING CHALLENGES

Many challenges arose from adapting previous project-based practices to remote training. For instance, 2020's students gave us feedback saying that although project-based learning was appealing and engaging for remote learning, they missed more active discussions with the other classmates about their ideas and implementation journey. For example, in face-to-face meetings, the coursework outline included more group discussions on related literature items, technical documentation review, and class discussion after each presentation. In the 2021 session, we decided to implement a "video always-on" policy since we had only 9 participants online. However, scenarios like the UOIT 2020's classes with 65 students would make it hard to adopt such a policy. We also included practical activities weekly to stimulate active participation, such as group discussion, individual and collective oral presentations, and monitored teamwork.

Figure 39 shows screenshots of the adapted Brainstorming ToyUI dynamic using a free browser plugin to simulate the *breakout rooms* feature in the *Google Meet*. The *breakout rooms* feature supported 48 minutes brainstorming session – we timed sessions in 18-6-6-6-12 minutes. The instructors could switch between rooms to speak with the teams individually and communicate the same information to all rooms concomitantly. For research purposes, it was also possible to record individual rooms to assess students' activities. The online setting did not seem to impact the overall dynamics negatively, and a few creators suggested that using a similar approach in other design projects would be welcome. Creators often expressed positive comments about the brainstorming dynamics during evaluation, such as *"very good," "sensational,"* and *"fun."* A 2021 creator stated, *"even though it was not possible to create an elaborated idea at the time, it served to explore creativity and help when it comes to generate ideas."* We replicated this strategy in the first low-fidelity prototyping session using the Stickers ToyUI and Storyboard Robot Ideas. Perhaps, the same feature can support group discussion sessions and monitored remote work in larger class sizes.

Figure 39 – Screenshots of online brainstorming session during 2021 evaluation.



Source: Author.

In 2016, creators had to determine their prototypes' technical specifications, which impacted the complexity of the ToyUI setups. As a result, their initial concepts expected more ToyUI components and play features than the final versions. An interesting finding is that creators faced similar challenges when developing their digital prototypes using the robot simulator *Zenbo Lab*. This tool offers block-coding or *Python* editor to implement applications for a virtual 3D robot embodiment. The simulator also connects with the physical robot embodiment to install the application in the Robot Operating System

(ROS). Although limited, the *Zenbo Lab* simulator allows the virtual robot to reproduce multimedia files in the robot's screen thumbnail and computer speakers. It also simulates voice-based interaction as text balloons and text-input, simulate robot movement and navigation through 3D animation, and change the virtual wheels' colors. The robot embodiment's functions not supported by the virtual robot include following the line (using the color sensor) and processing multimedia input (object or marker detection).

Once creators did not have access to the physical robot, they could not implement more complex HRI tasks such as integrating the companion robot with physical toy components or companion device applications. In the 2020 sessions, we tried to implement the students' simulator files (ZBA files) in the physical robot *Zenbo Junior* and send weekly feedback. However, the gap between simulated behaviors and actual robot embodiment was far from our expectations. While working in the simulator with the physical robot, one can easily update, test, and correct miss behaviors as they go, but when the full implementation depends on the remote setting, correcting and sometimes identifying the mistakes can become a tiresome task. We had to evaluate the student's work based on the simulator behaviors to be fair during the assessment.

In the 2021 survey, all creators stated that they wished to access the physical robot to test and implement HRI behaviors during the HCD stages. The following creator's statement reflecting this frustration experience is related to the Brainstorming ToyUI evaluation. *"One thing that left me a bit frustrated was that we had several innovative ideas that later ended up being cut because there were several questions about how they would be implemented (in the robot), which left us a bit lost because we did not really have direct contact with the robot and its tools."* We also noticed that the lack of a physical embodiment for testing is of significant importance when planning robot embodiment features. Features, such as robot movement (e.g., neck and navigation), visual cues (e.g., lighting and synchronizing LED), voice interaction, and multimedia inputs (e.g., fiducial markers, object detection, and face recognition) were often overlooked when implementing the digital prototypes.

As the robot *Zenbo Junior* incorporates a touchscreen, many creators prioritized the same design cues from mobile applications (e.g., touching for selecting options and navigating between screens). Although screen interaction can reduce the amount of sensitive and PD collection, they lack interactivity aspects that a companion robot can offer to CCI. An aspect that had a significant impact during most remote training was that we could not perform user testing sessions, which may have compromised the prototypes' overall quality. In past evaluations, the presence of specialists and end-users have improved the projects significantly. In many cases, creators had to rely on user research through reviewing related works and inspirational artifacts. Fortunately, we invited specialists to review project presentations and provide feedback during all remote 2020's classes, which was helpful. Although the 2021 session managed to adapt some user-centric evaluation strategies in the remote setting. Still, it is necessary to implement strategies to conduct user evaluation with end-users using either the robot simulator or remote interaction with the physical robot in future efforts.

6.5 FINAL DISCUSSIONS

This chapter provided a detailed critical discussion of six-year stakeholders' evaluation, including recent data on remote training during the COVID-19 pandemic. The ToyUI Toolkit offers a diverse collection of HCD tools to CCI creators, guiding them from seeking inspiration, generating context-oriented ideas, and quickly implementing them using user-centric strategies. Despite the discussed research limitations, this thesis implemented an appropriate *treatment design* using the Design Science Methodology (DSM), satisfying the identified stakeholders' needs and goals (WIERINGA, 2014).

7 THESIS CONTRIBUTIONS

This research thesis addresses the research problem of supporting interdisciplinary teams and creators in designing integrated Toy User Interface (ToyUI) solutions for Child-Computer Interaction (CCI). The primary goal was developing a collection of design tools to support training them in essential User Experience (UX) design skills and Information Technology (IT) skills, supporting them in problem-solving and decision-making processes in different stages of system development (e.g., user research, ideation, data collection planning, and rapid prototyping). The **ToyUI Toolkit** addresses these aspects by intervening from early to advanced Human-Centered Design (HCD) stages – covering inspiration, ideation, and implementation stages. This final chapter summarizes this thesis' scientific contributions to state-of-the-art in CCI, remarks the conclusions considering research limitations, and suggests opportunities for future works.

7.1 SCIENTIFIC CONTRIBUTIONS

This thesis' contents are extensively published in CCI, Human-Computer Interaction (HCI), Internet of Things (IoT)-related international conferences and journals. A chronological list of the primary scientific contributions appears below.

- **Toy User Interfaces: Systematic and Industrial Mapping**, *Journal of Systems Architecture* (Received: 10 April 2018, Revised: 16 October 2018, Accepted: 1 December 2018, Available online: 3 December 2018) (ALBUQUERQUE; KELNER, 2018)

- **Non-personal Data Collection for Toy User Interfaces**, *Proceedings of the 52nd Hawaii International Conference on System Sciences*, (8 January 2019) (ALBUQUERQUE; KELNER, 2019)

- **Human-Centered Design Tools for Smart Toys**, *9th IEEE International Symposium on Cloud and Service Computing* (18 November 2019) (ALBUQUERQUE; KELNER; HUNG, 2019)

- **IoT4Fun Rapid Prototyping Toolkit for Smart Toys**, *Proceedings of the 53rd Hawaii International Conference on System Sciences* (7 January 2020) (ALBUQUERQUE et al., 2020)

- **IoT4Fun Rapid Prototyping Tools for Toy User Interfaces**, *Electronic Commerce Research and Applications* (Received: 1 January 2020, Revised: 27 June 2020, Accepted: 22 September 2020, Available online: 28 September 2020) (WHELER et al., 2020)

- **Toy User Interface Design — Tools for Child-Computer Interaction**, *International Journal of Child-Computer Interaction* (Received: 30 October 2020, Revised: 25 March 2021, Accepted: 17 April 2021, Available online: 24 April 2021) (WHELER et al., 2021)

The performance of this research thesis has promoted collaboration with other CCI researchers and data security experts, resulting in the following secondary scientific contributions.

- **A Privacy-Preserving Context Ontology (PPCO) for Smart Connected Toys**, *2019 12th CMI Conference on Cybersecurity and Privacy* (28 November 2019) (YANKSON et al., 2019a)
- **Privacy in smart toys: Risks and proposed solutions**, *Electronic Commerce Research and Applications* (Received: 1 May 2019, Revised: 10 November 2019, Accepted: 10 November 2019, Available online: 13 December 2019) (ALBUQUERQUE et al., 2020)
- **A Literature Survey on Smart Toy-related Children's Privacy Risks**, *Proceedings of the 53rd Hawaii International Conference on System Sciences* (7 January 2020) (FANTINATO et al., 2020)
- **Guitar Tuner and Song Performance Evaluation Using a NAO robot**, *2020 Workshop on Robotics in Education* (11 September 2020 – Best Paper Award). (MELO et al., 2020)
- **Preliminary Tendencies of Users' Expectations about Privacy on Connected-Autonomous Vehicles**, *2020 IEEE International Conference on Systems, Man, and Cybernetics* (10 November 2020) (SALGADO et al., 2020)

7.2 CONCLUSIONS

CCI can be introduced since the first stages of child development, opening opportunities to engage children in CCI activities while facilitating parental monitoring tasks. The complexity and number of CCI artifacts grow more attractive over the years, raising concerns for the parents regarding screen-time consumption and online privacy risks. Adequate methods and tools to design, implement, and evaluate CCI artifacts play a significant role in ensuring those benefits while mitigating potential risks during system development. Toolkit design supports aligning new solutions to existing UX design and IT infrastructure and standards, enabling replication and creative exploration. This research successfully achieved the primary research goal of delivering an adequate treatment design that can support training those essential skills in interdisciplinary stakeholders –

the ToyUI Toolkit. This thesis provides detailed descriptions to implement and use the ToyUI Toolkit, including making available the digital versions online [1]. Overall, this thesis addressed all stated research goals as follows.

- Classified the related literature on integrated CCI artifacts conducting a systematic mapping covering 163 research publications from 2008–2021, and an Industry mapping classifying information from 160 CCI companies.
- Proposed seven design tools supporting HCD problem-solving approach after reviewing and taking lessons from related literature and CCI industries.
- Successfully incorporated privacy by design principles supporting decision-making on data management aspects and rapid prototyping as part of the ToyUI Toolkit.
- Evaluated a diverse HCI toolkit with 255 interdisciplinary stakeholders across three countries in seven institutions, incorporating all necessary improvements and generating iterative versions of each HCD tool.
- Adapted the ToyUI Toolkit to support remote training and learning, implementing and evaluating digital tool versions during the COVID-19 pandemic.

The first thesis' contribution to the CCI research community and industries is the ToyUI definition and classification, delivering a robust terminology that encompasses a diversity of computing technologies and plays interactions. There is no previous classification covering both play and interface aspects in the related literature. Therefore, the feature-based classification model was also extracted from the mapped items. The setup integration of one or more physical toy components with other hardware or software components constitutes a ToyUI setup. A ToyUI setup can integrate various hardware and software technologies, including Augmented Reality (AR) and other Mixed-Reality (MR) applications, Human-Robot Interaction (HRI) applications, sensory-based and IoT applications, speech recognition and Artificial Intelligence (AI) applications, and location-based applications. The ToyUI model classifies this diverse context into 22 ToyUI setups, eight genres, and four categories. The Children's Play & Games (CPG) category reassemble traditional toy and play features by using technology to enhance CCI experiences. The Games & Applications for Fun (GAF) category mixes physical and digital components and offers more closed-play rules, such as board games, card games, and agile game mechanics. Meanwhile, Interactive Social Toys (IST) and Serious Games & Applications (SGA) categories explore content-driven play and promote HRI features by introducing companion robot components as play mediators and active social actors. The ToyUI classification permits organizing items based on their play and interactive features and supports creators in understanding available design spaces. In the CCI industries, this

[1] http://www.iot4fun.com/

classification can also support toy companies and retailers in better displaying products and communicating the benefits of hardware-software integrated products for multiple target audiences.

Bridging the gap between physical and virtual play remains challenging, especially when delivering integrated CCI experiences to the users and ensuring children's privacy rights to Personal Data (PD) protection. The goals behind collecting, managing, and storing user data, including PD, are varied. In many situations containing PD like Global Positioning System (GPS) becomes necessary to support essential CCI tasks. A significant research problem is providing the CCI community with adequate tools to support decision-making during data collection planning and system development stages. The second contribution of this thesis is the non-PD model. Only three types of non-PD are suitable for both object and user tracking in ToyUI design: Non-Personal Identification (NPID), Unidentifiable Positioning System (UPS), and Motion Tracking. When adopting a strict non-PD collection strategy to develop ToyUI setups, creators can limit collecting PD and sensitive data, minimizing potential harm to children's privacy in the face of implied data-breach vulnerabilities. Although data minimization can support mitigating risks to children's privacy, it does not exclude the need to implement other privacy by design principles and establish appropriate infrastructure for data protection. Therefore, this thesis implements the non-PD strategy, incorporating and critically relating research on data security and privacy protection standards.

There is limited information on how CCI industries use HCD and other design tools to support the development of ToyUI setups. In several circumstances, the design process and results are, to some extent, experimental, and CCI industries are still learning how to develop integrated CCI experiences while seeking suitable design practices. Most existing vulnerabilities in ToyUI setups are easily correctable with existing IoT resources and likely related to the creator's decisions on cybersecurity practices. Related literature suggests intervening in the early stages of system development, and that decision-making tools can potentially assist creators in overcoming these issues. This thesis' main contribution is the ToyUI Toolkit, developed through the lenses of the Design Science Methodology (DSM) framework. The proposed HCD tools support a systematic, integrated, and iterative problem-solving process using individual and collaborative tools to support interdisciplinary teams in decision-making during system development. The idea is to integrate them in the sense that the first stage tools output can provide sufficient input to the next stage, and so on. ToyUI creators are designers, engineers, developers, and other IT, marketing, and business professionals, including IT outsourcing. Other stakeholders are the children, parents, educators, therapists, and several private, governmental, and non-for-profit institutions. The ToyUI Toolkit supports training creators' UX design skills like problem-solving and decision-making, and IT skills on data collection planning and management. The HCD tools intervene in different system development stages from inspiration, ideation, and implementation, covering steps from the user research, brainstorming sessions, data management planning, and low to high-fidelity prototyping of the ToyUI setups.

This thesis introduces seven original tools (i.e., ToyUI classification, brainstorming ToyUI, data collection planning, storyboard robot ideas, stickers ToyUI, MiMi AI Robot, and IoT4Fun toolkit) and adapts supporting tools from the literature (i.e., ToyUI Design Document, System Usability Scale (SUS), and SUS-Kids) (RYAN, 1999; BANGOR; KORTUM; MILLER, 2008; PUTNAM et al., 2020). Novel HCD tools can become part of the ToyUI toolkit as it evolves in future works. First, the ToyUI Classification tool supports conducting a feature-based analysis of ToyUI setups to address context investigation and user research. The Brainstorming ToyUI generates ideas based on toys and game features, and creative constraints. Data Collection Planning tool help creators to classify ideas based on potential privacy and security issues and overcome vulnerabilities by adopting a non-PD strategy. The Robot Storyboard Ideas supports detailing HRI ideas including robot embodiment and user research information. The Stickers ToyUI use paper-based embodiment, sensors, and actuators to support low-fidelity prototyping. MiMi AI Robot permits implementing and testing AI features using open-source resources and a low-cost robot embodiment. Finally, the IoT4Fun Toolkit is a rapid prototyping toolkit based on non-PD approach that facilitates hardware and software integration.

Stakeholders' evaluation from 2016 to 2021 in seven Brazilian, Canadian, and German institutions assessed the ToyUI Toolkit usage and adequacy in the HCD stages, including its adaptability, robustness, and completeness to support generating innovative ToyUI setups. Evaluation strategies included demonstration and usage evaluation strategies in a series of case studies. In most cases, evaluation occurred in long-term usage evaluations in post-secondary institutions with graduate students. Short sessions included workshops in public events with designers, engineers, and computer science professionals. Regarding data analysis strategies, the treatment evaluation mixed different qualitative assessment methods. This thesis opted to employ summative content analysis strategies to assess the creators' working materials by counting and comparing keywords and relating them with the problem context. Usage evaluation also includes data from usability testing of creators' projects with secondary stakeholders, analysis of iterative technical documentation, creators' feedback on teamwork experience. Altogether, 255 interdisciplinary stakeholders among professionals, undergraduate students, and graduate students experienced different versions of the ToyUI Toolkit, implementing 67 ideas among low and high-fidelity prototypes and digital prototypes. Results discussion presents evidence on the ToyUI Toolkit usage and how case studies supported improving each HCD tool over the years.

In summary, the ToyUI Classification tool helps creators in the inspiration stage by training skills in ToyUI and CCI topics and assessing features from inspirational artifacts. The Brainstorming ToyUI tool supports group discussion in ideation stage by offering resources to creators to generate and polish ideas while training tangibility and UX design aspects, such as problem-solving. The Data Collection Planning tools support the careful handling of data management that prioritizes non-PD strategy against PD and sensitive data strategies. However, implementation strategies significantly impact data security practices adopted by creators and final decision making. The Robot Storyboard Ideas facilitates idea presentation and planning HRI tasks for the ToyUI setups, which was also helpful to collect user feedback in remote sessions with parents and children. The Stickers ToyUI tool facilitates low-fidelity prototyping sessions in the implementation stage by simplifying technical concepts and permitting creators to plan and test the ToyUI setup's features before functional implementation. The rapid prototyping tools IoT4Fun Toolkit and MiMi AI Robot allow the fast development and testing of new ToyUI setup ideas. The IoT4Fun Toolkit successfully limits data collection to non-PD strategy (i.e., motion tracking, UPS, and NPID) and its modularity features support fitting into various toy components. The MiMi AI app and robot embodiment offer resources to incorporate social CCI contents for the ToyUI setups by delivering open-source and low-cost solutions for both creators and institutions, but more data still necessary to prove its suitability for various ToyUI setups. Relating data security practices and implementation strategies adopted by the creators, a combined effort in all HCD stages becomes essential to ensure better decision-making practices.

Finally, several evaluation challenges emerged related to remote learning during social distancing, mainly when working with digital prototypes to simulate companion robots' physical embodiment behaviors. The evaluation of remote training raised concerns on the lack of tangible resources and how to perform user-centric evaluations with stakeholders remotely. This thesis contributes to addressing remote learning challenges by offering digital resources that support remote teamwork with interdisciplinary stakeholders. Also, the thesis contributes with preliminary user assessment strategies to collect user feedback with parents and children, strategies to perform remote monitored practical activities, such as online brainstorming and low-fidelity prototyping sessions, and stimulate stakeholders' social interaction and active participation during remote learning. Conclusively, the ToyUI Toolkit demonstrates a suitable approach to support the CCI research community during in-person and remote teamwork activities. Study limitations must account for the lack of user assessment with CCI industry professionals and other research challenges associated with the COVID-19 pandemic, such as reduced user evaluation during remote training and the missing evaluation using the final versions of implementation tools (i.e., the IoT4Fun Toolkit V3, MiMi AI Robot V2, and the Rapid Coding Tool (RCT) Software Development Kit (SDK)). We could not perform the necessary integration tests supporting all hardware functionalities and integration using the RCT SDK. Testing required working with materials available only in the research facilities at Universidade Federal de Pernambuco (UFPE). Similar to other institutions, UFPE moved all academic activities to remote settings since early 2020. The training of interdisciplinary stakeholders in a post-secondary setting can assist the CCI industries by offering training of human resources, including best UX design practices for IT outsourcing companies.

7.3 FUTURE WORKS

This research thesis offers many opportunities for future works since CCI is a promising research field with many practical challenges and a growing interest from the research community, related industries, and society. Immediate research efforts intend to compare the full version of the ToyUI Toolkit in remote learning and face-to-face meetings. The A/B approach was practical to evaluate the toolkit's usefulness and adequacy, but a full curriculum implementation using the ToyUI Toolkit may conquer a robust assessment and fair evaluation by delivering the full extent of the toolkit's benefits to stakeholders. Moreover, reaching out to CCI companies is a research goal to evaluate the HCD tools with industry professionals and marketing-oriented product development. The principal investigator intends to contact the 160 mapped CCI companies and other identified stakeholders (e.g., Toy Association and other non-for-profit institutions) to surveyed them and provide an easy guide for ToyUI design and the digital tools targeting creative teams and supporting collaboration through IT outsourcing.

Motivations to introduce tools for creators include reducing authoring time and complexity when designing new ToyUI setups, defining pathways to design solutions that overcome existing issues, and empowering new audiences (LEDO et al., 2018). There are plans to continue using the HCD tools with graduate and undergraduate students since the ToyUI Toolkit's several benefits to support a project-based learning curriculum in HCI post-secondary education (THURSTON et al., 2017; EL-GABRY, 2018). Implementing the RCT SDK integrated with the IoT4Fun Toolkit V3 and MiMi AI Robot V2 can also support future participatory and co-design sessions with non-experts, such as Science, Technology, Engineering, and Mathematics (STEM) educators, child therapists, and parents (KNOWLES et al., 2019; WOOD et al., 2019; AUSTIN et al., 2020).

Also, modularizing and standardizing coding features, such as developing a block coding language and other visual language modeling strategies, can empower children and youth audiences to become ToyUI designers and building an inclusive and integrated AI-based curriculum from kindergarten, primary, and secondary education (YAROSH; SCHUELLER, 2017; BJÖRLING; ROSE, 2019; GENNARI et al., 2019; WILLIAMS; PARK; BREAZEAL, 2019; KARA; CAGILTAY, 2020; KEWALRAMANI et al., 2020; SABUNCUOGLU, 2020). Moreover, adapting coding interfaces using the IoT4Fun Toolkit features can support implementing an inclusive and tangible block coding tool for the visually impaired community (DORSEY; PARK; HOWARD, 2014; JAFRI; ALJUHANI; ALI, 2015; NAMDEV; MAES, 2015; TALIB et al., 2018; MILNE; LADNER, 2019; CANDELA, 2019), including providing resources to participatory design sessions with inclusive groups of users (REGAL et al., 2020; VERVER et al., 2020; GÜLDENPFENNIG; FIKAR; GANHÖR, 2018; CANO et al., 2018).

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