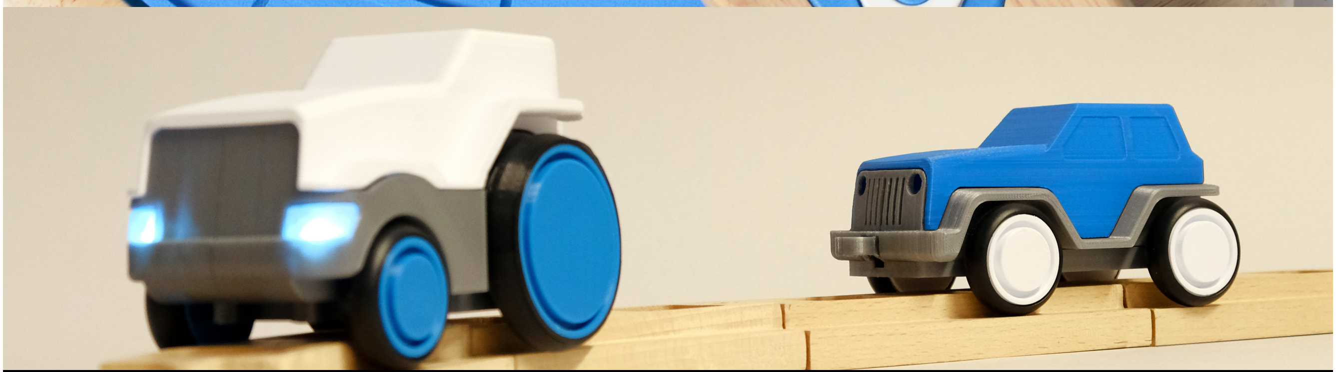
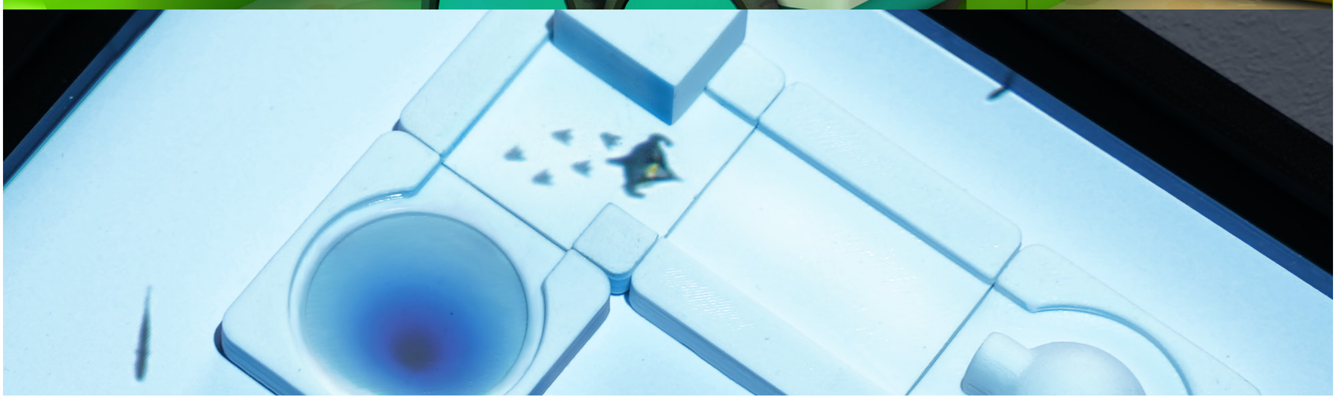


EMBODIED INTERACTION IN A WORLD FULL OF DISPLAYS

MARIEKE VAN CAMP



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DOCTORAL DISSERTATION

submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy (PhD) in Product Development at

University of Antwerp,
Faculty of Design Sciences,
Department of Product Development

Antwerp, 2022

to be defended by Marieke Van Camp,
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Embodied interaction in a world full of displays

Van Camp, M. (2022). Embodied interaction in a world full of displays. University of Antwerp.

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Acknowledgements

I would like to thank:

My supervisor Lukas Van Campenhout for introducing me to the topics of this thesis, for his confidence in the approach taken, and for all the inspiration. My supervisor Regan Watts for giving me the opportunity and freedom to work on my own topic for four years. Guido De Bruyne for the regularly follow-up at the start of my PhD, for passing on your knowledge about the different funding channels, and for showing your appreciation for the effort that I put into my work.

Herbert Peremans and Uta Pottgiesser who have been chair during different points of the research. Ingrid Moons for taking over their responsibilities and for always being reachable in the final defence stage.

Dirk Van Gogh for all the moral support and kindness.

Jouke Verlinden for involving me in other research projects and for encouraging my exchange plans.

Thomas Peeters, Muriel De Boeck, Jochen Vleugels, Shriram Mukunthan, Raman Garimella, Lore Veelaert, and Laure Herweyers for going on our long, individual PhD journeys together.

An additional thank you to Jochen Vleugels for answering my technical questions and for everything you do for the research group and for the students.

In the last seven years I have enjoyed the opportunity to work with many students. I especially want to thank those students who have contributed to this thesis. A big thank you to Cedric Lodewijckx, Thomas Verstrepen, Rob Uyttersprot, Eva Van Emelen, Anthony Collin, Christophe Demarbaix, and Jasper Verschuren. It was a pleasure working with you all!

A big thank you to the external jury members: Joep Frens and Anna Vallgårda for showing interest in my work, for sharing your expertise, and for always responding to my emails so quickly. You both have been very helpful, flexible, and supportive.

An additional thank you to Anna Vallgårda and her team for giving me the opportunity to experience how research is done in another research group.

Dilys Cosemans for helping out with the practical organization and the formalities of the defence.

I would also like to thank the people from Beuk & Noot, Mozaïek, and de Krokodil for their contributions to the user study.

Thank you Tristan ‘Ohm Meta’ Vloeberghs for letting me use your music in the videos!

I owe a big thank you to all my friends for keeping me sane all these years, for listening, and for getting me through the too many frustrating and disappointing moments of this PhD. And of course, my sisters – Marleen, Lies, and Tinne – my brother Jan and my parents for their endless support. Let’s celebrate now!

Sponsor acknowledgments: Funding has been provided by the Flemish Agency for Innovation and Entrepreneurship, also known as VLAIO (project number 150303) and by CLICS NV. Later I received a Dehousse scholarship from the University of Antwerp, Faculty of Design Sciences.

Summary

This PhD thesis titled “Embodied interaction in a world full of displays” presents a future vision for designing digital products. Our world is flooded with digital products. Our interaction with these digital products is standardized and largely restricted to the four corners of a display. Usually we interact with these digital products by tapping on icons that are displayed in the Graphical User Interface (GUI). This poorly corresponds with how we as humans naturally interact in the real world.

The overall goal of the thesis is to employ embodied interaction to explore and propose new ways to interact with digital products that more closely resemble our natural way of interacting in the real world.

Embodied interaction is a broad field which can be approached in various ways and from different perspectives. The initial research program adopts a token-based interaction approach. Token-based interaction is an early and basic form of tangible interaction which strives to embody digital information in physical objects or tokens. Token-based interaction is employed here within a context of children's toys in order to seek tangible alternatives for playing games on a tablet. The research program aims for full tangibility in children's toys by replacing all graphically-displayed digital information with tokens. This objective is based on the assumption that Tangible User Interfaces (TUIs) offer various benefits for children. Multiple prototypes of children's toys with a token-based TUI were developed and tested. After conducting several experiments, the research program was confronted with the limitations of token-based interaction. In addition, the added value of GUIs could no longer be denied. As such, the research program moved away from its initial strive for full tangibility in children's toys and decided to look into the possibilities of hybrid interaction to seek an advantageous combination between TUIs and GUIs. The next experiment shows that striking the right balance is key to successfully combining TUIs and GUIs in one toy.

Because the terms 'TUI' and 'GUI' do not fully grasp this idea, a new research program is developed. The new research program does not hold on to the terms 'TUI' and 'GUI', but instead proposes the concept of two halves: a physical half which consists of physical content and a graphical half which consists of graphical content. The research program is based on the assumption that when both halves are together and combined in the right way, they produce a better effect than when they are separate. A new framework is proposed called the hybrid synergy

framework which offers three themes or ways to achieve such a synergistic effect between the physical half and the graphical half of digital products. The causality theme draws on the impossible, trompe-l'œil-like effect which emerges when physical content and graphical content seemingly interact on each other. The unification theme is based on the assumption that by letting physical content and graphical content work together as one, a more natural or intuitive interaction with digital products can be achieved. And finally, the transformation theme aims for the magical, surprising experience which occurs when physical content and graphical content seemingly transform into one another. Finally, a new concept is introduced, the Content Specific Display. A Content Specific Display is a display that is tailored to a single type of content. Because a Content Specific Display can reflect a physical commitment to the displayed graphical content, it can sustain the continuous balancing act between physical content and graphical content. As such, it can be used as a medium or a tool to reach a synergistic effect between physical content and graphical content. Further experiments enabled the development of several demonstrators which present the concepts of the research program. Next to children's toys, the concepts are demonstrated in other product applications.

The whole inquiry process is led by a Research through Design (RtD) method. This thesis illustrates and explores a particular kind of RtD, one which acknowledges the evolving and transitional character of RtD. The RtD process consists of multiple experiments which are driven by the research program. The research program formed a foundation for carrying out the experiments. However, instead of starting from a fixed and predetermined research program, the research program was influenced and challenged by the experiments themselves, and changed along the way.

Samenvatting

Deze doctoraatsthesis getiteld "Embodied interaction in a world full of displays" presenteert een nieuwe visie op het ontwerpen van digitale producten. Onze wereld wordt immers overspoeld met digitale producten. Onze interactie met deze digitale producten is gestandaardiseerd en beperkt zich tot het uitvoeren van handelingen op een scherm. Gewoonlijk interageren we met deze digitale producten door op iconen te tikken die worden weergegeven in de grafische gebruikersinterface. Dit stemt niet overeen met hoe we ons in de echte wereld gedragen.

In deze thesis wordt embodied interaction gebruikt om nieuwe interactiemogelijkheden voor digitale producten te onderzoeken die beter aansluiten met onze natuurlijke manier van handelen in de echte wereld. Embodied interaction is echter een ruim begrip en kan op verschillende manieren benaderd worden.

Het initiële onderzoeksprogramma is gebaseerd op de concepten van token-based interaction. Token-based interaction is een eenvoudige vorm van tangible interaction en streeft er naar om digitale informatie tastbaar te maken door het te belichamen in fysieke objecten of tokens. Token-based interaction wordt hier toegepast om fysiek kinderspeelgoed te ontwikkelen als alternatief voor het spelen van spelletjes op een tablet. Het onderzoeksprogramma gaat er van uit dat fysiek speelgoed vele voordelen biedt voor kinderen en streeft er daarom naar om alle grafische elementen op een scherm te vervangen door tokens. Er werden meerdere prototypes van gedigitaliseerd kinderspeelgoed ontwikkeld en getest. Na het uitvoeren van verschillende experimenten werd het onderzoeksprogramma echter geconfronteerd met de beperkingen van token-based interaction. Daarnaast viel ook de meerwaarde van grafische gebruikersinterfaces niet meer te ontkennen. Hierdoor stapte het onderzoeksprogramma af van het idee om volledig fysiek kinderspeelgoed te ontwerpen om zo de mogelijkheden van hybride speelgoed te kunnen onderzoeken. Het volgende experiment toont aan dat het belangrijk is om een goede balans te vinden tussen de zogenaamde tastbare en grafische gebruikersinterface bij het ontwerpen van hybride speelgoed. Omdat de termen tastbare en grafische gebruikersinterface de specificiteit van het onderzoeksprogramma niet meer voldoende omvatten, werd er een nieuw onderzoeksprogramma geformuleerd. Binnen het nieuwe onderzoeksprogramma wordt er niet meer gesproken van tastbare en grafische gebruikersinterfaces, maar wordt er voorgesteld om te werken met twee helften: een fysieke helft die bestaat

uit fysieke elementen en een grafische helft die bestaat uit grafische elementen. Wanneer beide helften samen zijn en op de juiste manier worden gecombineerd, dan zouden zij een beter effect bekomen dan wanneer zij gescheiden zijn. Het hybrid synergy framework omvat drie werkwijzen of thema's voor het bekomen van een dergelijk synergetisch effect tussen fysieke en grafische elementen. Het causality thema streeft naar een onmogelijke, trompe-l'œil achtige illusie die wordt veroorzaakt wanneer fysieke en grafische elementen schijnbaar op elkaar inwerken. Het unifcation thema is gesteund op de veronderstelling dat door fysieke elementen en grafische elementen als één geheel te laten samenwerken, een meer natuurlijke of intuïtieve interactie met digitale producten kan worden bereikt. Het transformation thema, ten slotte, is gericht op de magische, verrassende ervaring die optreedt wanneer fysieke en grafische elementen lijken in elkaar te transformeren. Tenslotte wordt een nieuw concept voorgesteld, de Content Specific Display. Een Content Specific Display is een beeldscherm dat slechts één type grafisch beeldmateriaal ondersteunt. Hierdoor kan zijn fysieke vorm vormgegeven worden naar het grafisch beeldmateriaal. Bijgevolg, laat de Content Specific Display ontwerpers toe om fysieke en grafische elementen volledig op elkaar af te stemmen en om een synergie tussen beide te bereiken. De Content Specific Display is dus een middel om een synergie tussen fysieke en grafische elementen te bekomen. Er werden verschillende prototypes ontwikkeld die de concepten van het onderzoeksprogramma presenteren. Naast kinderspeelgoed werden deze concepten ook gebruikt in andere product toepassingen.

Binnen dit onderzoek werd een Research through Design (RtD) methode gebruikt. Er werd een specifieke vorm van RtD gebruikt, een die openstaat voor het veranderlijke karakter van ontwerpend onderzoek en gebruik maakt van het voortschrijdend inzicht opgedaan tijdens het onderzoek. Het RtD proces bestaat uit meerdere experimenten die vanuit het onderzoeksprogramma worden uitgevoerd. Het onderzoeksprogramma werd niet vooraf vastgelegd, maar werd gaandeweg ontwikkeld en beïnvloed door de experimenten.

Chapter one: Introduction

1.1 Signs of the times: COVID-19 causing an upward change in screen use

This thesis was written in the midst of the COVID-19 pandemic. This pandemic has caused an unforeseen global crisis and will probably shape the world for years to come. The COVID-19 crisis prompted many governments, particularly in Europe, to introduce unprecedented measures to contain the pandemic (Han et al., 2020). These imposed restrictions, such as temporary closure of stores, bars and restaurants, social distancing rules, contact restrictions, curfew rules, and the limitation of non-essential travel, have limited people's ability to connect and physically interact. As a result people have increased their dependence on computers and other digital devices like tablets and smartphones causing an upward change in screen use (Sultana et al., 2021; Wong et al., 2021).

The following developments illustrate how people have replaced many facets of pre-pandemic life with online alternatives. Due to the pandemic people increasingly relied on remote video communication. Working from home has made applications such as Microsoft Teams, Zoom, Skype, and Blackboard Collaborate indispensable. These platforms are used for online meetings, online classes and student coaching, and online conference sessions, but people are also increasingly using these platforms in their leisure time for the virtual dinner party, live stream DJ sets and performances, and the online yoga course (Roose, 2020). Because the crises has halted physical shopping, the retail sector is particularly badly affected by the crisis (Ceylan, Ozkan, & Mulazimogullari, 2020). E-commerce businesses, on the contrary, are booming. Smaller businesses in particular should follow and offer their products online to protect themselves against crises (Beckers, Weekx, Beutels, & Verhetsel, 2021). This also counts for restaurants and caterers which now offer ordering and delivery services online. More and more people are taking the plunge to use the services of online platforms such as Netflix, dating applications, and health and lifestyle applications in order to replace social activities with online pastime. During the lockdown and curfew periods, many people replaced time spent on hobbies, exercise, and conversation with screen time. Young and elderly people and those who live alone are particularly vulnerable to loneliness and isolation and seek for online social interaction (Lippke, Fischer, & Ratz, 2021).

Some of these newly-learnt digital habits are expected to stay once the crisis is over (Sheth, 2020). For example, remote working saves one the trouble of driving or catching public transport to work every morning and makes one win a lot of time which is otherwise spent commuting. This has led to lower traffic congestion levels than before the introduction of the lockdown measures. Due to less traffic, the CO_2 emissions reduced and fewer pollutants are released into the air, thus improving the air quality (Papale et al., 2020). Furthermore, for some this global collective pause offered an opportunity to question and re-assess priorities. Personally I have experienced a greater sense of calm, less daily rush, and fewer social commitments.

Doing everything online, behind a display, has many advantages when it comes to organizing one's life in a more efficient and flexible way. Yet, the current situation caused by COVID-19 also accentuated some of the limitations related to increased screen use. This is illustrated below with an example from my personal experience.

Due to the pandemic, I had to coach my students online for the User Experience (UX) design project taught in the Bachelor’s program of Product Development at the University of Antwerp. Coaching the students online was more difficult, as it is not possible to grasp the student's cardboard mock-ups, or to see their sketches presented together on the table. This thwarted a direct discussion and made it difficult to convey feedback on their designs. Everything had to be explained in words, without using the mock-ups to explain something, or without making a quick sketch on paper. Also not being able to see the expressions of the students and their body language while going over the results, caused that I missed information about the present situation. Normally, I can sense if the students understood my feedback, now I was never sure if the message really sank in. Another striking thing is that many students indicated that they experienced more workload and higher levels of stress. However, the curriculum had not been changed compared to the previous year. Obviously for many students the whole crisis has caused feelings of anxiety and stress. But they might felt overwhelmed because working behind the computer all day can easily become stressful and energy-draining. Also, when the design courses were again organized on campus, all students were happy to see their peers again. Meeting friends online isn’t quite the same as meeting in person.

This example from my personal experience merely frames the larger context of the thesis and describes the signs of the times. It explains how people have replaced many facets of pre-pandemic life with online or 'on-screen' alternatives. It also shows how people's real-world activities cannot simply be replaced with screen time.

1.2 Designing for interaction

This thesis is based within industrial design and is concerned with the design of digital products [1]. There are many aspects to the design of digital products. This thesis is about designing for interaction. When designing for interaction, aspects of temporality and behaviour are added to the design practice (Frens & Hengeveld, 2013). Or in other words, interaction designers are not only ought to design the static form and function of a product, but they are primarily concerned with how our interaction with the product plays out over time.

1.3 A world full of displays

People's interaction with today's generation of digital products is largely restricted to the four corners of a display [2]. In fact, it is no exaggeration to say that displays have changed the face of industrial design. Displays determine how people interact with digital products and are omnipresent. Displays now cover the face of most of today's digital products. Displays are essential components of computers. Beyond computers, they are used in many handheld digital devices such as gaming devices, tablets, and smartphones. Other than that, they are used in all kinds of digital products, be it washing machines, microwaves, cars, etc. In addition, displays are commonly used in larger systems and machines such as printers and copy machines, production lines, and manufacturing systems. One can also find them in public and commercial places, hidden in bank terminals, ticket machines, and self-scan checkouts. Displays are valued for their ability to display digital information in graphically-appealing ways, for their dynamic character, and their excellent portability. By now, the total number of displays has passed the double-digit billion mark globally and their popularity is even increasing (Esser & Giessen, 2020).

That displays have changed the face of industrial design is well depicted in Figure 1 and Figure 2. Today's digital products largely depend on their built-in displays to make digital information available to the user. Other than their omnipresence, there are two other striking things.

1. First, all displays have the same form-factor. When it comes to displays there currently seems to be only one golden standard defined by its flat, rectangular, and rigid form. However, over the next few years, the form

factor will diversify and display technology [3] such as Head Mounted Displays (HMD) for Virtual Reality (VR) or Augmented Reality (AR) applications, foldables, retinal projections, 3D holograms or direct projections (e.g., onto car windows), are expected to be adopted in different environments and use cases (Esser & Giessen, 2020). Examples of such next-generation displays and display technology are presented in chapter seven.

2. Second, in all the examples digital information is displayed in a similar fashion via a Graphical User Interface (GUI). This is discussed further in the next section.

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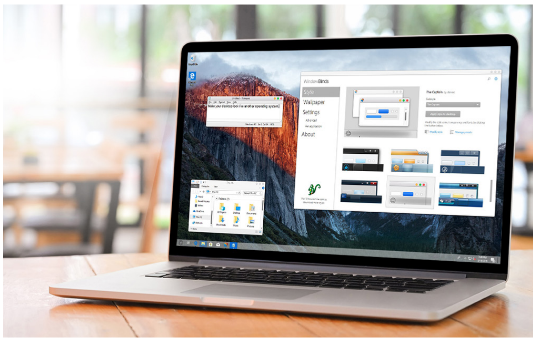
[1] In this thesis a digital product refers to any interactive, consumer product with built-in computer or embedded processor. Today, products such as microwaves, dishwashers, children's toys, and cars are designed to embed digital technology. Digital products offer additional features and functionalities compared to non-digital, analog products and their computing power rivals that of previous generation desktop computers. This thesis is based within industrial design and is only concerned with tangible, consumer products that are enhanced with digital technology. Software and services are often referred to as digital products as well, but these are not the type of products this thesis is concerned with.
This thesis is not concerned with designing the interaction of analog products. Analog products are interactive but do not incorporate digital technology. Analog products are mechanical or electromechanical products such as typewriters, analog cameras, and analog corded telephones without digital display and computer board.
Nor is this thesis about the design of non-interactive products such as chairs, tables, or knives.

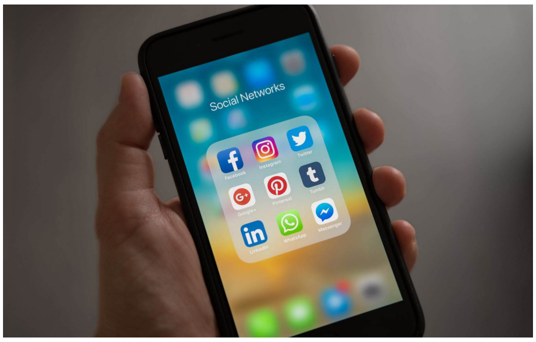
[2] A display can refer to anything showing something. For example, mannequins in a shop window can form a display or cardboard displays used for product display are called displays as well. However, these are not the type of displays this thesis is concerned with.
This thesis is concerned with those displays with integrated light sources, e.g., Light Emitting Diodes (LED) that are used for displaying graphical content. A display can be part of a product (e.g., the display integrated in a washing machine) or can stand on its own (e.g., billboard displays). A display can be tiny, like just displaying hours and minutes on a watch or showing the numbers on a calculator. A display can be very large, like the ones mounted on the walls of buildings used for advertising.
A screen is a particular implementation of a display and refers to any flat surface displaying graphical content. For example, movie theatres have a projector and a large screen, but also a smartphone consists of a glass screen. The term 'screen' is generally used today as a synonym for display and people now commonly use the terms 'screen time' and 'screen use'. This thesis sticks to the term 'display' but adopts the terms 'screen time' and 'screen use'.

[3] Other than conventional displays, the field of display technology covers a large collection of technologies such as Head Up Displays (HUD), HMD, etc., that all focus on displaying graphical content.




performance icon
PFAFF


METROID


Social Networks


Haier

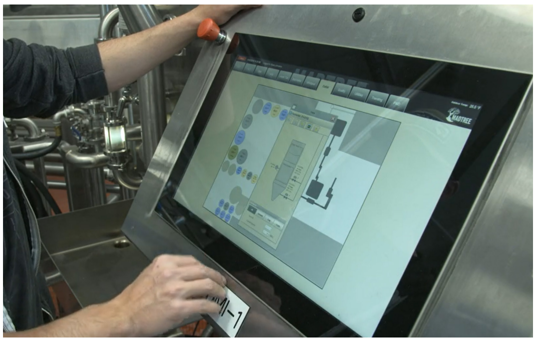


Figure 1 Left page: the top row shows a Macbook Pro, equipped with a Retina display that supports vivid colours and high image quality (left) and the PFAFF performance icon sewing machine with multi-touch display (right). Next is the Nintendo Switch handheld gaming device that offers the traditional, video game experience on a pocket size display (left) and the iPhone with multi-touch display (right). The next row shows a washing machine with built-in multi-touch display that displays the GUI with the different washing programs (left) and the interior of a Tesla model 3 which replaces all physical, driver controls with a central multi-touch display (right). The bottom row shows an example of an espresso machine with multi-touch display (left) and an example of a display used in a production line as the system's central operating unit. Pictures taken from Stardock, n.d.; Pfaff, n.d.; Pocket-lint, 2021; Morningside, 2018; Haier, n.d.; Tesla, n.d.; Pertazza, n.d.; Inductive automation, 2018.

Figure 2 Right page: shows a ticket terminal with multi-touch display used for buying printed public transport tickets (left) and a self-scan terminal with multi-touch display used in a supermarket (right). Pictures taken from MIVB.brussels, n.d.; Yelp, 2015.

1.4 The dominant GUI paradigm

Displays are commonly used in digital products to make digital information graphically available to humans via a GUI. The GUI is the dominant paradigm for interactions with digital systems for almost three decades now (Zerega Bravo, 2013). Designers are basing most of the applications being developed today on the GUI design (Ibid). In a GUI digital information is made visually perceivable and accessible to humans by spatially arranging graphical content over the display's surface. The graphical content displayed in today's GUIs are visual metaphors such as windows, menus, tool bars, tabs, buttons, and icons. These visual metaphors take familiar concepts from the physical world to make digital information understandable to humans. For example, in a GUI, dropping a file in a desktop trash can is equivalent to deleting the file. Moreover, a window refers to the English word 'window' and literally is a rectangular area surrounded by a window frame that enables the user to look into a separate file, location, or folder. The actions in a GUI are performed through manipulation of these visual metaphors. One can use their finger, a keyboard, or a mouse, or any other pointing device to work with these visual metaphors.

GUIs are preferred for their versatile and graphically-appealing interfaces and are universally applicable, well thought-out interfaces. However, despite their ubiquity and longevity many researchers have formulated their critique on the GUI (van Dam, 2000). This section describes some of the main concerns that underpin this thesis.

A first concern is that today's GUIs rely mainly on people's cognitive skills and completely neglect people's physical skills (Djajadiningrat, Matthews, & Stienstra, 2007; Figueroa & Juárez-Ramírez, 2017). GUIs are said to capitalize on people's ability to read, interpret and remember information, but do not exploit people's wide range of physical skills and familiarity with the physical world (Dourish, 2001, p. 102). Because of this, the GUI runs the risk of becoming cognitively overwhelming. This is often the case for advanced or complex tasks or in interfaces that are cluttered with information (Allen et al., 2001; Jung, Wiltse, Wiberg, & Stolterman, 2017; Papacharalampopoulos, Giannoulis, Stavropoulos, & Mourtzis, 2020; Xia, 2020). Furthermore, by relying solely on people's cognitive skills and not stimulating people's bodies enough, GUIs are often very monotonous and repetitive to use (Bodin, Berglund, & Forsman, 2019).

Second, the GUI is often criticized for "being generic and not sensitive to the particular nature or character of some given piece of information or specific act of use" (Redström, 2008). The GUI was originally developed for the desktop PC which has to cater for many different tasks, hence its generality. But besides the desktop PC, the GUI is now used in various other digital products and systems (Djajadiningrat, Wensveen, Frens, & Overbeeke, 2004). Because of this, digital products often look highly similar and provide the same, standardized interaction (Ibid; Van Campenhout et al., 2016). The generic interaction style of the GUI is beneficial for multi-purpose systems such as computers, tablets, and smartphones which have to present a range of different functions and applications, but is particularly weak when applied to single-purpose products. These single-purpose products require specialized or 'strong specific' solutions that are attuned to the specific functionality of the product. The 'weak general' GUI may do the job, yet in a less favourable way.

A third point is that the GUI displays digital information such that it is detached from its surroundings, rather than displaying digital information as an integral part of the environment in which it is being put to use (Ishii & Ullmer, 1997; Ong, Wang, & Nee, 2020). This is for example the case for in-vehicle GPS systems, in which information such as navigation instructions, warnings, and travel time are not displayed directly on the car's windshield to match with the road reality, but in which the information is presented on the vehicle's built-in display. Separating the information from its contextual surroundings, causes the GPS system to not match with the action of driving a car. The information is not directly mapped onto the passing scenery in the driver's field of view, but instead the driver needs to move his/her attention away from the road to take in information. Such systems are not only distracting and unsafe to use (Ramnath, Kinnear, Chowdhury, & Hyatt, 2020), but poorly correspond to the way the driver interacts in his/her physical environment (Osswald, 2013; Riener & Wintersberger, 2011).

Other critiques on the GUI point to shortcomings in usability. Svanæs, Alsos, and Dahl (2010) argue that the GUI is a common source of usability problems in all Information Communications Technology (ICT) systems, and that many of the usability problems caused by the GUI have their roots in a mismatch between the GUI and human cognition. Especially older people experience difficulties understanding the GUI structures, which cannot be solved merely through the use of large fonts, icons, and buttons (Zhou, Chourasia, & Vanderheiden, 2016).

1.5 Research perspectives

Traditional HCI and Cartesian dualism

Arguably most of the concerns related to GUI specific issues come from a long tradition of Cartesian dualism in Human-Computer Interaction (HCI). This is because, at the time the GUI was first introduced, traditional HCI defined the design of all digital systems. Traditional HCI is rooted in cognitive science as well as in ergonomics and human factors engineering (Hurtienne, 2009). From cognitive sciences traditional HCI inherited the Cartesian understanding that mental processes and physical interaction are separate (Marshall & Hornecker, 2013). Traditional HCI focuses on the cognitive processes involved in one's interaction with digital technology[4] (Carroll, 1997), and is concerned with designing interfaces which are attuned to the human mind. However, the existence of the human body, as well as the physical world in which the human body is situated, is totally denied in traditional HCI. This is well depicted in Figure 3. The figure shows how traditional HCI ignores the role of the human body in people's interaction with computers and instead treats the mind as some sort of central, human processor.

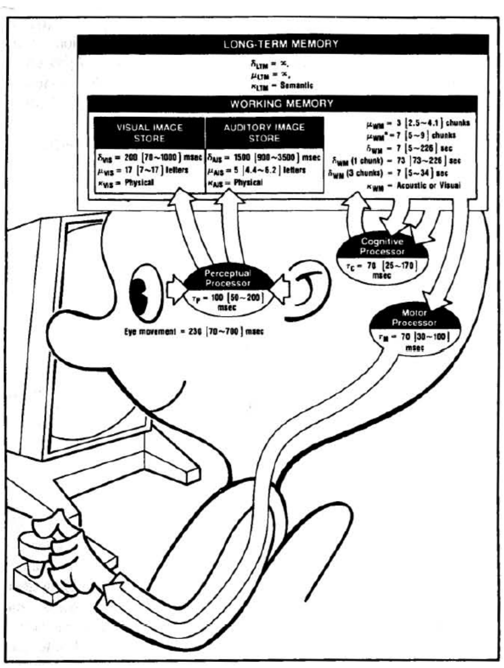


Figure 3 This picture illustrates how in traditional HCI the brain is seen as the central processing unit of the human body. Picture courtesy of Card, Newell, and Moran, 1983.

Third wave of HCI and phenomenology

Over the last two to three decades a wide variety of approaches have emerged that appear to fit poorly the models and methods from traditional HCI (Harrison et al., 2007). These approaches fall under the third wave of HCI, which includes approaches such as ubiquitous computing (Weiser, 1991), embodied interaction (Dourish, 2001), affective computing (Picard, 2000), and calm technology (Weiser & Brown, 1997). The central claim behind all these approaches is that thinking is not analogous to information processing (Harrison, Tatar, & Sengers, 2007) and that it is not merely an activity of the mind, but it is grounded in humans sensorimotor interaction with the environment. These ideas have an origin in phenomenological philosophy (Gunkel, 2018). Accordingly, the third wave of HCI draws heavily on the work of philosophers such as Husserl, Heidegger, and Merleau-Ponty [5]. In contrast to traditional HCI, the third wave of HCI aims to include all human abilities (perceptual-motor, emotional, and social skills) in people's interaction with digital technology. Third wave HCI relies on the body-in-action as opposed to traditional HCI which merely focuses on cognition. Third-wave HCI is concerned with people's interaction in the world around them, taking place in the local, situated contexts of everyday life. Next to its phenomenological backdrop the third wave of HCI seems to be defined in terms of a focus on the cultural aspects of digital technology, the expansion of the cognitive to the emotional, and a shift from strictly pragmatic (usefulness, efficiency, performance) to hedonic (joy, fun, pleasure) values (Bødker, 2006).

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[4] *The term 'computational technology' is often used in HCI. This thesis does not use the term 'computational technology' but instead uses the term 'digital technology'. This is because today computation is inescapably connected to the ones and zeros of digital logic. The same goes for the term 'computational system' for which this thesis uses the term 'digital system'.*

Digital system is a broad term and can refer to elements such as hardware, software and networks. It is used in this thesis to refer to computers (laptops and desktops) (1); all handheld digital devices such as handheld gaming devices, tablets, smartphones (2); wearables such as smartwatches (3); other digital products with built-in computer or microcontroller such as washing machines, digital toys, and cars (4); larger digital systems such as production lines, and Internet of Things (IoT) based systems (5).

[5] *The influence of the work of philosophers such as Husserl, Heidegger, Schutz's, and Merleau-Ponty on HCI has been broadly described in Dourish (2001).*

Embodied interaction

As discussed, this thesis draws inspiration from one of the perspectives of the third wave of HCI in particular, embodied interaction. Dourish (2001) defines embodied interaction as interaction with digital systems that occupy a world of physical and social reality, and that exploit this fact in how they interact with people (Ibid, p. 14). Dourish says that digital systems should not be treated as separate from their physical and social environments in which they are put to use. Embodied interaction draws together ideas from two areas of research: tangible computing and social computing (Ibid, p. 55). This thesis mostly focuses on the tangible aspects related to embodied interaction. Tangible computing is concerned with how digital technology can be better integrated in the physical environment and employs physicality to the design of digital systems that exploit human perceptual-motor and tactile skills. Tangible computing is a broad umbrella description for a range of research fields united through an interest in the role of physicality (Hornecker, 2011).

Tangible interaction

The ideas of tangible computing are similar to the vision originally presented in Ishii's and Ullmer's (1997) paper 'tangible bits'. This paper laid the foundation for the movement which is called 'tangible interaction'. Back then tangible interaction was a radical new vision on HCI which centres on coupling digital information or bits to everyday, physical objects, in order to bridge the gap between the physical world and the digital world. Concretely this is done by giving digital information physical form (Hornecker & Buur, 2006) or, in other words, by embodying digital information in physical objects (Ullmer, Ishii, & Jacob, 2005). While a GUI serves as a window through which one can reach into a digital world, a Tangible User Interface (TUI) is part of the same physical world in which people live and interact. Unlike graphical content, physical objects are tangible and directly graspable and offer a range of physical properties.

The concepts of tangible interaction are best illustrated with an example. One such an example is Topobo (Parkes, Raffle, & Ishii, 2008). Topobo is a robotic construction toy with kinetic memory. The building blocks of the Topobo system have the ability to record and playback physical motion. The child can program the behaviour of their construction by twisting, bending, and pulling the physical building blocks. The construction immediately goes into playback mode, and starts to replay the recorded movement. Digital technology is directly embedded in the building blocks in order to enable children to program the behaviour of their constructions through natural, physical actions, instead of using a separate GUI (Raffle, Parkes, & Ishii, 2004). An example of a robotic construction made with the building blocks of the Topobo construction toy is shown below in Figure 4.

Figure 4 The picture shows someone's hands holding a robotic construction made with the building blocks of the Topobo construction toy. Picture courtesy of Tangible Media Group, MIT Media Lab.

Experiment one to experiment three of this thesis look into a specific form of tangible interaction, namely token-based interaction. In token-based interaction a physical object is used to access digital information that is stored outside the object. Such objects are called tokens (Holmquist, Redström, & Ljungstrand, 1999). These tokens are not in themselves interactive, that is, they do not have their own battery or do not contain any actuated components. They instead act as physical tags. They are merely used to physically represent digital information. The digital information that is associated to the token can be physically represented by the shape, colour, size, and material of the token. MediaBlocks is a well-known example of such a token-based system (Ullmer, Ishii, & Glas, 1998). MediaBlocks consists of small, electronically tagged wooden blocks. The wooden blocks basically are physical tags that allow to transport and rapidly copy digital information from one device to another (Ibid). Technologies such as RFID and NFC have facilitated the adoption of tokens in commercial applications. An example of a commercial application with a token-based TUI is Jooki, a music player for children from the Belgian company Muuselabs (Jooki, n.d.). The music player has multiple physical figurines or tokens (Figure 5). The child's parents can connect a song or playlist to each of the figurines in Spotify. When the tokens are connected to Spotify, the child only has to place the token on the Jooki for the song or playlist to start. This idea of having these interactive, physical figurines or tokens has also been adopted in Activision's Skylanders Imaginators (Activision, n.d.), Disney Infinity, and LEGO dimensions. The latter two are not available anymore and the official websites have been taken offline.

Figure 5 Jooki a music player for children with tokens. Picture courtesy of Muuselabs.

LEGO DUPLO came up with a more creative use of tokens. LEGO DUPLO developed a programmable toy train with tokens. The tokens are placed into the slots of the train track. The toy train reads and responds to the tokens. With the tokens children can control the toy train (e.g., the red token makes the toy train stop for a few seconds). This concept from LEGO DUPLO led to the development of a new LEGO Education line (see Figure 6).

Figure 6 A picture of the LEGO Education toy train coding express set which is based on the LEGO DUPLO toy train set with tokens. Picture courtesy of LEGO.

1.6 Case study of the thesis

As the previously mentioned examples indicate, a relatively large proportion of research in tangible interaction has concerned applications for children (Holmquist et al., 2019). The relevance of TUIs for children's education was pointed out even before the emergence of the term 'TUI' (Zaman, Vanden Abeele, Markopoulos, & Marshall, 2012). For example, the team led by Mitchel Resnick at MIT Media Lab was already working on the development of what they called digital manipulatives: digitally enhanced versions of traditional children's toys (Resnick et al., 1998) before the term 'tangible interaction' was first coined by Ishii and Ullmer in 1997. This led to a successful collaboration with LEGO which resulted in the development of the LEGO MINDSTORMS line in the late 90s (Resnick, Martin, Sargent, & Silverman, 1996).

Tangible interaction has been linked to various benefits for children (Zaman, Vanden Abeele, Markopoulos, & Marshall, 2012). Firstly, tangibility has often been associated with intuitive usability, due to the naturalness of manipulating physical objects which capitalize on children's innate skills (Fjeld, Schar, Signorello, & Krueger, 2002; Patten & Ishii, 2000). Secondly, TUIs may positively affect children's learning performance, which may arise through links between concrete, physical manipulations and cognition (Horn, 2018; Marshall, 2007). Thirdly, TUIs are said to be more fun to use than more traditional kinds of interfaces (Verhaegh, Hoonhout, & Fontijn, 2007; Xie, Antle, & Motamedi, 2008). Finally, TUIs are said to stimulate collaborative activity between children (Africano et al., 2004; Angelini, Mugellini, Khaled, & Couture, 2018; Cohen, Withgott, & Piernot, 1999; Stanton et al., 2001).

The relevance of tangible interaction for children becomes even more apparent as handheld digital devices are starting to play an increasingly important role in young children's lives. Especially, tablets and smartphones seem to be very popular among young children and are being widely used for playing games. The average time young children spend using these handheld digital devices is increasing (Radesky, Schumacher, & Zuckerman, 2015; Herodotou, 2018). In the United States, the amount of time children between the age of zero and eight spend on tablets and smartphones has greatly increased in a decade. In 2020 children from birth to age eight on average spend about two and a half hours (2:24) on tablets and smartphones a day (Rideout & Robb, 2020). In 2017, this age group on average spent 48 minutes per day using tablets and smartphones, compared to 15 minutes per day in 2013 and five minutes in 2011 (Rideout, 2017).

This trend of increased screen time by young children is followed worldwide. Similar increases have been observed in other locations such as South Korea (Chang et al., 2018), Australia (Rhodes, 2017), and various West European nations (Chaudron, Di Gioia, & Gemo, 2018; Ofcom, 2016).

The effects of screen time on the physiological and psychological development of young children is still unclear and studies in the past report both positive and negative effects (Domingues-Montanari, 2017). However, ask most parents with young children and they will probably say they are worried about letting their children play on tablets and smartphones for longer periods of time. Accordingly, many parents make unpopular decisions like limiting their children's daily screen time. Also teachers warn that rising numbers of children are unable to perform other physical play skills such as using building blocks because of overexposure to tablets (Paton, 2014; Read et al., 2018). TUIs may provide an attractive and more responsible alternative to playing games on tablets and smartphones, as they combine the rich affordances and manipulative capabilities of traditional toys, while allowing a more versatile and stimulating play experience.

In the later stages of the research, the context is extended beyond children's toys to include other product applications.

1.7 Contributions

The key contributions of the research are explored in the different experiments and are distributed over the remaining chapters of the thesis.

The first contribution is a specific kind of token-based interaction, where tokens are considered as means for physical activity, instead of using tokens merely for physical representation of digital information, like it is done in early tangible interaction. Experiment one to three provide examples of how tokens are used as interactive building blocks in different children's toys. The results show how tokens can offer possibilities for digitally enhancing constructive play. In the presented examples tokens are specifically employed for composing children's melodies.

The following part of the research takes a different direction and led to the development of a new framework, called the hybrid synergy framework (see chapter six). The hybrid synergy framework builds on and contributes to the concept of coupling which is employed in the interaction frogger framework (Wensveen, Djajadiningrat, & Overbeeke, 2004) to achieve a more natural and intuitive interaction in digital products, and in the aesthetics of coupling framework (Van Campenhout, Frens, Vaes, & Hummels, 2020) to establish a particular form of aesthetics in digital products. The hybrid synergy framework is positioned as a framework for designing digital products. The hybrid synergy framework strives for an engaging interaction and experience induced through the synergistic interplay between the graphical content displayed on the product's display and the physical components of the product, also referred to in this thesis as physical content. Now the GUI displayed on the product's display is often designed separately from the rest of the product, and not by industrial designers but by software developers and UI/UX designers. The hybrid synergy framework posits the importance of designing the displayed graphical content in parallel and in synergy with the rest of the product.

The idea of developing specialized, single-purpose displays contributes to the endeavour of realizing such a synergy. Namely, synergy can only occur when the distinct product halves can get really close to one another. And, in order to get closer to one another, they need to meet each other's specific characteristics as best they can. With this idea in mind, a new kind of display is proposed, called the Content Specific Display. In experiment five to nine, examples of Content Specific Displays are used in different product applications.

Finally, the research contributes by outlining Research through Design (RtD) as a gradually-evolving inquiry process where insights are derived through the interaction between the experiments and the overarching research program. The research contributes to literature on programmatic design research.

1.8 Structure of the remainder of the thesis

This section briefly summarizes the introductory chapter. It restates the research goal and explains how the remaining chapters will explore this. The overall research goal is based on the current state of affairs in industrial design which has become increasingly a matter of designing the interfaces of digital products. The overall goal of the thesis is to employ embodied interaction and other related perspectives to propose alternatives to today's digital products. The remaining chapters are all oriented towards this goal.

Chapter two: Research method

A Research through Design (RtD) method is used to proceed towards the research goal. As such, chapter two introduces RtD as the main research method of this thesis. Chapter two explains how the research follows an evolving approach to RtD, according to the program/experiment dialectics approach described by Redström (2011) which is commonly referred to as programmatic design research. Programmatic design research is about establishing a research program through experimentation. Finally, chapter two briefly explains the overall evolution of the research program, before turning to the initial research program.

Chapter three: A precedent design project

Chapter three reports on the design results obtained from my MSc thesis which preceded this PhD research. This precedent design project investigates a token-based interaction perspective in the context of children's toys. The chapter reports on the iterative design process employed for the development of a prototype of a musical children's toy with a token-based TUI. The study enabled me to develop my initial stance on token-based interaction and sets a basis for the subsequent experiments.

Chapter four: Investigating a token-based interaction perspective

Chapter four reports on the results of the iterative design process in which iterative prototypes of a digital toy train are designed and evaluated in two experiments. A This-or-That and Laddering method were used to carry out comparative user evaluation studies with children aged five and six. The results of the evaluation helped to determine preference for the systems tested and to gain insight into the reasons for preference. Moreover, the results helped to formulate design recommendations to improve the interaction of the prototype. A first prototype of a digital toy train with a token-based TUI is designed in experiment two. The prototype is an adaptation from the previous prototype designed in experiment one, but offers more musical and interaction possibilities. The prototype was compared to a traditional toy train and a toy train game on a tablet. The results from the user evaluation show that the game on a tablet is most preferred since it supports many musical possibilities and subgames and offers a more stimulating play experience. In experiment three, two improved versions of the digital toy train prototype are designed. One version includes an extra set of tokens. The other version includes a graphical application running on a separate computer. Both versions are then compared to each other. The results from the user evaluation show that children prefer the digital toy train with extra tokens. Adding a graphical application to the prototype is not preferred, as the participants repeatedly had to switch between the digital toy train and the graphical application, which disrupted the interaction flow.

Chapter five: Investigating a hybrid interaction perspective

The previous chapter shows that digital toys with a token-based TUI and games on a tablet both have their distinct qualities and are preferred for different reasons. One cannot simply replace the other. Experiment three took a first step in combining them to combine their individual benefits, but the right balance was not found. Consequently, experiment four explores a hybrid interaction perspective in the context of children's toys. A prototype of a programming toy with a HUI is designed. The prototype combines a TUI and a GUI in order to take advantage of the strong points of each. Compared to the digital toy train prototype with graphical application designed in experiment three, the TUI and the GUI of the prototype designed in experiment four are not detached from each other but they are closer together. They are closer together not only spatially, but the TUI and the GUI also interact more closely with one another.

Chapter six: Hybrid synergy framework

This idea of striking a balance is taken further to the point where the TUI and the GUI are not considered as separate entities anymore, but almost merge together into one whole. However, instead of holding on to the terms 'TUI' and 'GUI' a new research program is developed which proposes the concept of two halves: a physical half and a graphical half. The new research program is founded on the assumption that when both halves are together and combined in the right way, they produce a better effect than when they are separate. This idea is formalized in a new framework, called the hybrid synergy framework. The hybrid synergy framework provides different ways or themes for exploiting the synergies between the physical half and the graphical half of digital products. A prototype of a children's puzzle is developed in experiment five to demonstrate a first theme.

Chapter seven: The Content Specific Display

Chapter seven focuses on finding a new medium needed to reach a synergistic effect between the physical half and the graphical half of digital products. Accordingly, chapter seven introduces a new concept, the Content Specific Display. A Content Specific display is a display that is tailored to a single type of content. The concept sustains the continuous balancing act between the physical half and the graphical half and allows to further investigate the synergies between them. To illustrate this, chapter seven presents four additional experiments that offer concrete examples of Content Specific Displays. Finally, this chapter discusses two additional hybrid synergy themes that arose from these experiments. All the examples that are presented in this chapter are results of student projects. These student projects enabled to further refine the research program and to investigate it outside the context of children's toys.

Chapter eight: Conclusion

Chapter eight gives a final description of the research program and explains it in a more general sense without explaining or elaborating the results of the experiments. Subsequently, the chapter discusses how the presented designs are embodied. The particularities and limitations of the methodological approach are discussed. Finally, directions for future research are suggested.

Chapter two: Research method

2.1 Introduction

This chapter introduces RtD as the main research method of this thesis. In this thesis a particular kind of RtD is used, one which acknowledges the evolving and transitional character of RtD. The evolving RtD trajectory is based on programmatic design research. The structure and components of programmatic design research are explained. An overview of the RtD process is given and the evolution of the programmatic process and the different experiments is described. Finally, the initial research program is given.

2.2 Research through Design

RtD is used as a broad umbrella term [6] for research practices that recognize the process of designing and making an artefact as a legitimate method of inquiry (Markussen, Bang, Pedersen, & Knutz, 2012). Or in other words, in RtD design practice is used as a tool for knowledge production. With design practice meaning a designerly way to deal with things, as in finding a possible solution through sketches and prototypes instead of theoretical reasoning (Stappers & Giaccardi, 2017).

RtD is not new, the term was first coined in Frayling's influential speech in 1993 at the Royal College of Art (RCA, London). Ever since RtD has been especially popular within design research (Stappers & Giaccardi, 2017) and other fields such as HCI (Bardzell, Bardzell, & Hansen, 2015), and Human-Robot Interaction (HRI) (Luria, Zimmerman, & Forlizzi, 2019).

RtD is valued for its explorative and generative qualities (Gaver, 2012), for its indispensable problem solving capacity (Horváth, 2007) which is particularly useful for tackling wicked problems (Zimmerman, Forlizzi, & Evenson, 2007), its

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[6] *Different views on how and for what RtD should be used, have led to the development of a range of varying approaches to RtD and even more approaches that go by labels other than the term 'RtD' (Andersen et al., 2019). Among these are Empirical RtD (Keyson & Bruns Alonso, 2009), Autoethnographical RtD (Chien & Hassenzahl, 2020), Experimental Design Research (Brandt & Binder, 2007), Design-Inclusive Research (Horváth, 2007), Constructive Design Research (Koskinen & Krogh, 2015), and Critical and Speculative Design (Dunne & Raby, 2013).*

ability to challenge and provoke critical reflection on the status quo by designing speculative objects (Zimmerman & Forlizzi, 2014), and its potential for ingraining new value systems and for opening up new design spaces (Gaver, 2011).

In this thesis, RtD is specifically employed for its innovative capacity and its ability to expose new possibilities which have been previously impossible, unrecognized or not yet thought of. The act of designing itself is here considered as an effective way to generate such new possibilities. The central idea behind the approach taken is that the knowledge which is implicitly present in the designer's intuition (Badke-Schaub & Eris, 2014; Van Campenhout, 2016, p. 20) cannot be derived through rational or analytical thinking, but can only be acquired through the act of designing. Meaning that new possibilities can emerge out of the curiosity and the intuition of the designer by letting the designer employ his/her design skills. This approach implies that doing precedes thinking or rather that doing is a way of thinking, and that research involves making something in a skilful and hands-on way. It is by conducting hands-on design experiments and reflecting on them, that new research opportunities can be exposed.

The RtD process presented in this thesis consist of multiple design experiments. These experiments are part of an evolving process, in which the antecedent experiment determines the scope of the subsequent one. Namely, after each experiment a new opportunity to start the next experiment was defined, and so the RtD process gradually evolved.

A detailed overview of the RtD process and the different experiments which were carried out in this research are presented in Figure 8.

2.3 Programmatic design research

To deal with the evolving and transitional nature of the research, a programmatic approach to design research was adopted. "The knowledge produced through programmatic design research is understood as contingent, intermediary knowledge, rather than generalising knowledge on a particular topic" (Homewood, 2020). This knowledge is framed within what is called a research program [7]. The research program offers a specific view on design, or a specific way of dealing with design. It serves as a framework for carrying out design experiments [8].

The research program does not necessarily come before the experiment. In many cases the experiments are conducted long before a more general framing has been articulated in a program (Redström, 2017). Thus, the relationship between program and experiment is more complex and dynamic. In programmatic design research, research program and experiment influence, challenge, and transform each other as the research process unfolds (Redström, 2011). In short, programmatic design research describes the practice of a research-program-in-the-making which is shaped by the projects or experiments themselves.

Figure 7 presents the programmatic design research structure in a visual overview. It shows how the research program provides a foundation for carrying out design experiments. Whereas the research program is a larger, overarching framework, a set of theories and concepts, the results of the experiments are specific designs [9]. These designs do not offer the same level of abstraction as the program, but provide concrete examples of the larger program. The experiments allow the further refinement and development of the program. The more design experiments are conducted within a given research program, the clearer and more precise the research program becomes. However, not all experiments may fit within the given frame of the program. This may demand the program to expand its boundaries or to change its initial focus. When the experiments are too far away and not comply with the initial view of the program anymore, the development of a new program may even be needed.

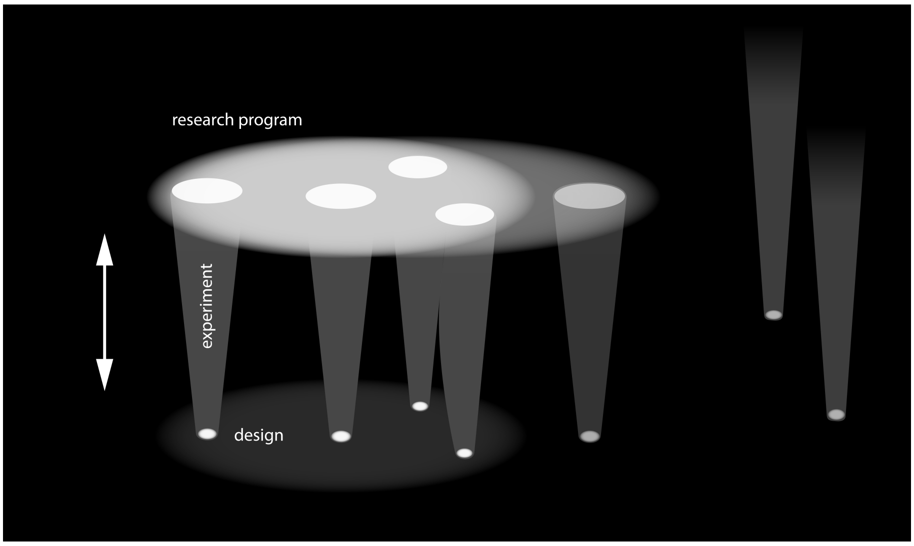

Figure 7 Shows how research program, experiment, and design relate to and differ from one another.

An easy way to think about programs and experiments, is to see them as different but interdependent sources of knowledge, which shed light in the dark.

The research program provides a broad and diffuse light source and provides more general knowledge on a topic.

The experiments are more specific, they are depicted in Figure 7 as spotlights which shed light on some of the vague areas of the larger program. When enough experiments are conducted, the knowledge which previously remained in the dark, becomes exposed.

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[7] *Research program: The term 'program' is used in accordance to the interpretation described in Redström (2011) and Redström (2017) with program meaning a specific view on design, or a specific way of dealing with design. A program describes the design principles, a set of theories, beliefs, articulations, and assumptions from which the designs are developed.*

A program provides the foundation or a framework for carrying out design experiments (Binder & Redström, 2006).

[8] *Experiment: an act or intervention intended to materialize, explore, or challenge a given program. Or an expression leading to the formulation of a program.*

It is important to note that the term 'experiment' is not used here in its traditional, scientific sense as a research practice/intervention in which one or more variables are consciously manipulated and the outcome or effect of that manipulation on other variables is observed. But instead experiment is used here in a more general sense linked to the creative process or action of trying out new ideas, methods, or activities.

This thesis follows the interpretation given by Redström (2017):

"The notion of an experiment is a complex topic and a debate as long as the history of research. Indeed, earlier in history, the notion of experimental method was more or less synonymous with scientific method, and for many, the typical image of a researcher is still a person in a lab coat. But the notion of experimentation holds more than this: experimental art, experimental vehicles, experimental living, and all sorts of activities conducted with the purpose of pushing boundaries and exploring alternatives. The understanding of the design experiment advocated here is rooted in the long history of labelling design that explores boundaries and alternatives as experimental - hence the notion that this is a kind of experimental design research."

[9] *Design: concrete result of the experiment. A concrete expression of the research program. The design demonstrates or represents the general ideas or concepts of the research program in a specific and concrete example.*

2.4 Evolution of the research program

Experiment one takes a first step in investigating a tangible and token-based interaction perspective in the context of children's toys. Experiment one preceded this research and has led to the formulation of an initial research program from which the subsequent experiments are carried out. In this thesis the initial research program is described in chapter two, before experiment one, since experiment one fits within that same program.

Experiment two to experiment four have challenged the research program and provided the necessary leverage to question some of the original arguments which were adopted from tangible and token-based interaction. This was needed to drift away from the program's original position within tangible and token-based interaction and to open the way to a hybrid interaction perspective.

However, as the process continued, the existing concepts and terminologies adopted from tangible and token-based interaction were not fitting or suited anymore to fully grasp the direction of the research. Therefore a new research program was formed which is described at the start of chapter five. Instead of using existing concepts and ideas, the new program proposes its own framework and concepts. Experiment five provides a first exploration and demonstration of the new program.

At a later stage, the research program was used within the educational program and further explored outside the context of children's toys. Experiment six to experiment nine are student work resulting from the research program. The results of the students enabled to further develop and refine the research program and to extend it to other product applications.

Finally, a final research program is described based on the results of the experiments. The final research program forms the main contribution of this thesis and is discussed in chapter eight.

Figure 8 gives an overview of the RtD process and the evolution of the research program. The experiments are ordered as they are in the thesis. The developed prototypes are numbered and named. The overview can be used as a guide while reading the thesis. The thesis returns to the overview to discuss the progress of the research after each experiment.

VOUWBLAD

Figure 8

the RtD overview will be printed on a folded page and can be found at the end of this pdf. document

VOUWBLAD

2.5 The initial research program

The initial research program is situated within a context of children's toys where a significant increase in screen time and reduce in physical play have been observed in the last decade due to the popularization of digital devices like tablets and smartphones which children now frequently use for playing games (see chapter one section 1.6). The research program plays within the field of tangible interaction and specifically adopts a token-based interaction approach where tokens are used to physically represent digital information. The research program aims for full tangibility in children's toys by replacing all graphically-displayed digital information with tokens. The motivation behind the objective to replace all graphical content with physical tokens, is based on the assumption that TUIs offer various benefits for children (see chapter one section 1.6).

Several experiments are conducted in which prototypes of children's toys with token-based TUIs are designed and compared to other GUI alternatives. The goal of the experiments is to design and propose token-based alternatives which can be put on par with their GUI counterparts.

To do so, the research program follows a more advanced understanding of token-based interaction than the one found in iconic examples of token-based systems such as mediaBlocks (Ullmer, Ishii, & Glas, 1998) or in commercial examples such as Jooki (Jooki, n.d.). The tokens in the designed prototypes are not used simply as storage media, but function as active components of the toy. Or in other words, the tokens are more than three-dimensional representations of digital information and are used as essential building blocks of the toy. The research program's initial stance on token-based interaction goes beyond the representational view (van Dijk, 2013) as found in early tangible interaction research, a vision most prominently put forward by Hiroshi Ishii and colleagues.

Chapter three: A precedent design project

Part of the results presented in chapter three are based on the paper Van Camp et al., 2019.

3.1 Introduction

Chapter three reports aspects of my MSc thesis which preceded my PhD research. This precedent design project is included as the first experiment of this thesis. This chapter reports on the iterative design process employed for the development of a prototype of a musical children's toy with a token-based TUI. The iterative design process is based on a cyclic process of prototyping, testing, analysing, and improving the prototype. The process continued until a final, user-ready prototype was reached. Three iterations of the prototype were required. The final prototype reflects my initial stance on token-based interaction.

3.2 Experiment one: concept design

The concept is inspired by the design of Digital Audio Workstations (DAW) such as Ableton live (Ableton, n.d.). Ableton live is a software which supports a large set of digital tools and sounds for music creation. One of the tools included in the software is a step sequencer (see Figure 9). A step sequencer consists of a series of looping rows in a grid where one can create musical patterns with software instruments. These rows are used to arrange notes in an ordered sequence. One can choose the location of each note and its length. It is basically a way to map the position of multiple sounds or notes in relation to the time of the beat. For example, if you divide a four bar loop in 4/4 time, it will have 16 beats, or steps (see Figure 9). You can then enter the location and length for, say, the kick drum on the steps you want it to play, and then do the same for the snare, and so on. When you then start the step sequencer, it will play all the marked out steps back at the given time.

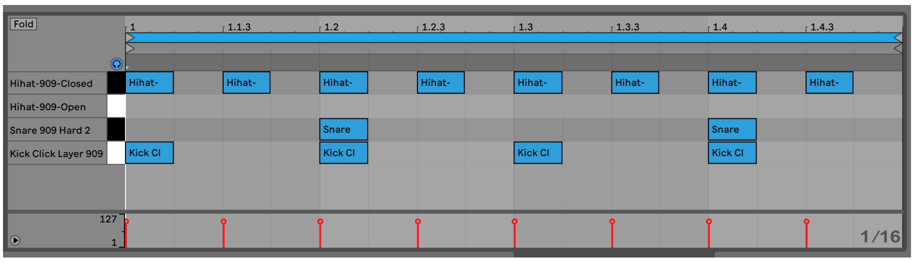

Figure 9 The step sequencer tool in the Ableton live interface.

A concept was designed of a digital toy which embodies the elements of the step sequencer's GUI in physical objects (see Figure 10). In this concept, the sequencer is built around a rotating turntable. In total five looping rows are included in the toy's turntable. Each row represents a different note or sound. Coin-shaped tokens are used to trigger these notes and sounds. By placing the tokens on the turntable and then manually rotating the turntable, children can create and play their own beat.

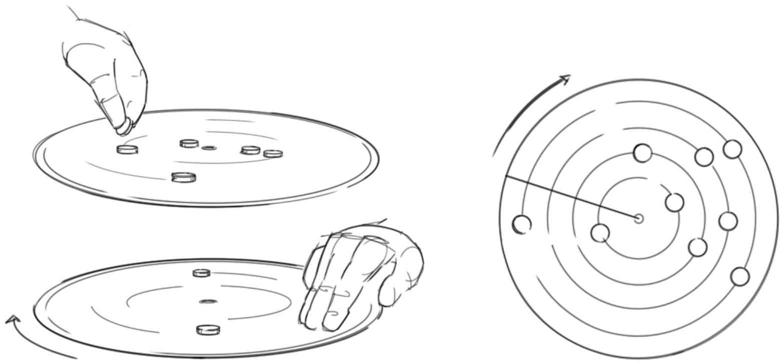

Figure 10 Sketches of the token-based sequencer concept. The sketches show how the coin-shaped tokens are placed on the turntable.

3.3 Experiment one: iteration one

A first prototype was constructed to monitor the sequential reading of the tokens. To construct the prototype, the turntable of a vinyl record player was used. To read out the values of the looping rows, five infrared transmitter-receiver sensors (model CNY70) were used. These infrared sensors are able to detect white objects that are placed on the black turntable surface. A separate part was modelled and 3D printed to enclose all the infrared sensors and to stagger them over the five rows. This part is placed right above the turntable's surface. An Arduino UNO microcontroller is used to read out the sensor values. The microcontroller is connected to a separate computer using a Musical Instrument Digital Interface (MIDI) to USB cable. These sensor values are then sent to and interpreted in Ableton live to trigger the corresponding audio samples each time a white object is detected.

Next to testing the reading of the sensor values, the usability of the prototype was tested. This led to multiple conclusions related to the prototype's usability. First, the turntable's Revolutions Per Minute (RPM) is too high. This makes one want to use their hand to slow down the turntable manually. This sometimes caused the drive belt to come loose. Not being able to adjust the tempo led to frustrations. Second, there are some issues with placing the tokens on the turntable. Often a token passed between two sensors and was not detected. Sometimes, the tokens moved because of the velocity of the turntable. The different looping rows must therefore be physically separated from each other. This way it is easier to correctly arrange the tokens. Plus all the tokens stay in place when the turntable is rotating. A picture of the prototype is shown below in Figure 11.

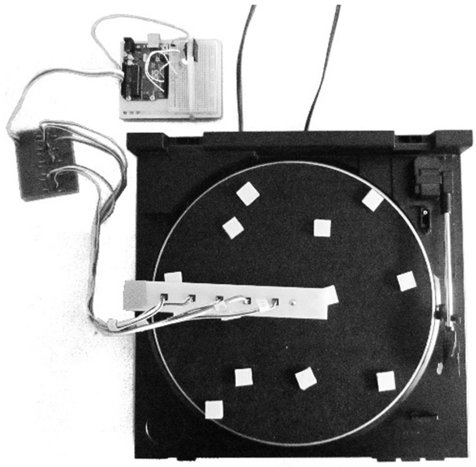

Figure 11 A first prototype of the token-based sequencer concept is made of a vinyl record player and includes infrared sensors that can detect the white tokens on the black turntable. The prototype is used to test the reading of the sensor values and the usability of the prototype.

3.4 Experiment one: iteration two

The aim of iteration two is to build a prototype that can be tested with children. To construct the prototype, the electronic parts which were verified in the first prototype were reused and integrated in the second prototype. Based on the insights gained from designing and testing the first prototype, some changes were made to the design. First, a dedicated turntable for the prototype was cut in Medium Density Fireboard (MDF) and painted black. Instead of using a motorized turntable, the turntable can be operated manually by rotating a lever.

The turntable is larger compared to the turntable of the first prototype, since the mechanical parts of the lever are integrated in the centre of the turntable's top surface. For the mechanical lever system parts of a salad spinner were used. The five looping rows in the turntable are separated from each other by interspaces of three millimetres thick. This way the tokens can be easily aligned with the position of the sensors. The coin-shaped tokens were cut out of MDF and painted white. Finally, the lever mechanism with turntable is connected to an overarching bridge to set up a floating platform for the prototype. This platform also includes the infrared sensors. A picture of the prototype is shown below in Figure 12.

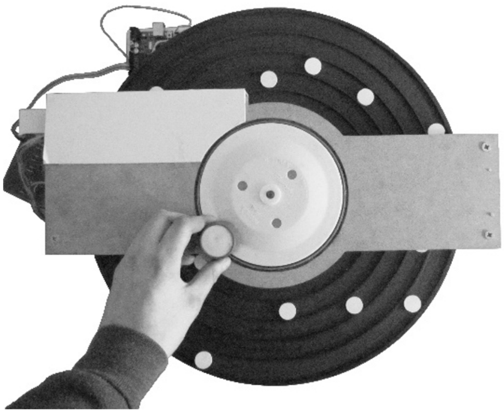

Figure 12 A second low-fidelity prototype is constructed in MDF. The prototype includes a lever mechanism in the centre of the turntable. The prototype is tested with children

User observations were conducted with the prototype. These user observations were carried out with children aged five and six attending early formal education. One class of one pre-primary school participated in the study. In total eight children (five boys, three girls) participated. The tests were conducted in groups rather than individual sessions. Group one included three children (one boy, two girls), group two included three children (three boys), and group three included two children (one boy, one girl). The school was informed regarding the study and written consent was obtained. The children had the opportunity not to participate in this study or to stop their participation in the study at any time. The user observations were conducted in a separate area of the classroom during class time. The computer and prototype were installed on a table. The participants were allowed to freely play with the prototype during the observation. The facilitator did not intervene during the observation and did not ask the participants any questions. The facilitator did make notes during the user observations. Figure 13 shows a picture taken during the user observations.

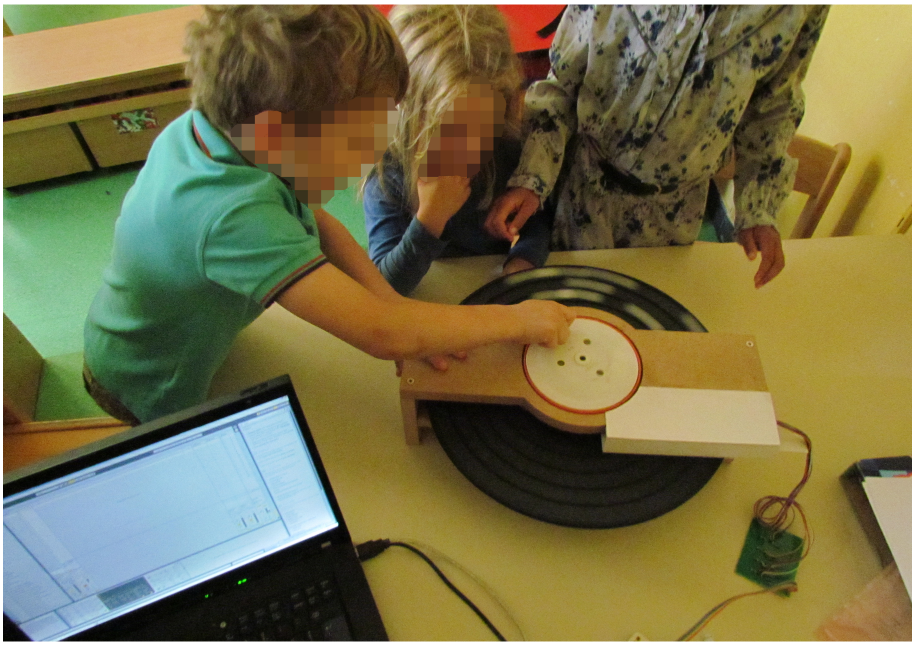

Figure 13 The participants of group one playing with the token-based sequencer prototype during the user observation.

Multiple conclusions from the user observations concerning the usability and interaction of the prototype were listed during the observations. First, the lever and the electronics need to be relocated to ensure a good view over the turntable surface with tokens. Now the overarching bridge blocks the view of the turntable's top surface. Second, the prototype needs to be designed in such a way that the turntable is not reachable from the sides. Now the children use these sides to control the rotating of the turntable, instead of using the lever. Third, a reduction gear box is needed to reduce the turntable's RPM. Namely, some participants enjoyed making the turntable rotate as fast as possible, causing the tokens to come out of the rows. Moreover, increasing the velocity of the turntable to such a degree causes the prototype to generate unpleasant noise. Fourth, the prototype must be more robust to allow children to play with it without the risk of breaking it.

Overall, the prototype was intuitively understood by each of the participants without further instructions. The lever affords a rotating like action. The tokens fit naturally in the slots of the looping rows.

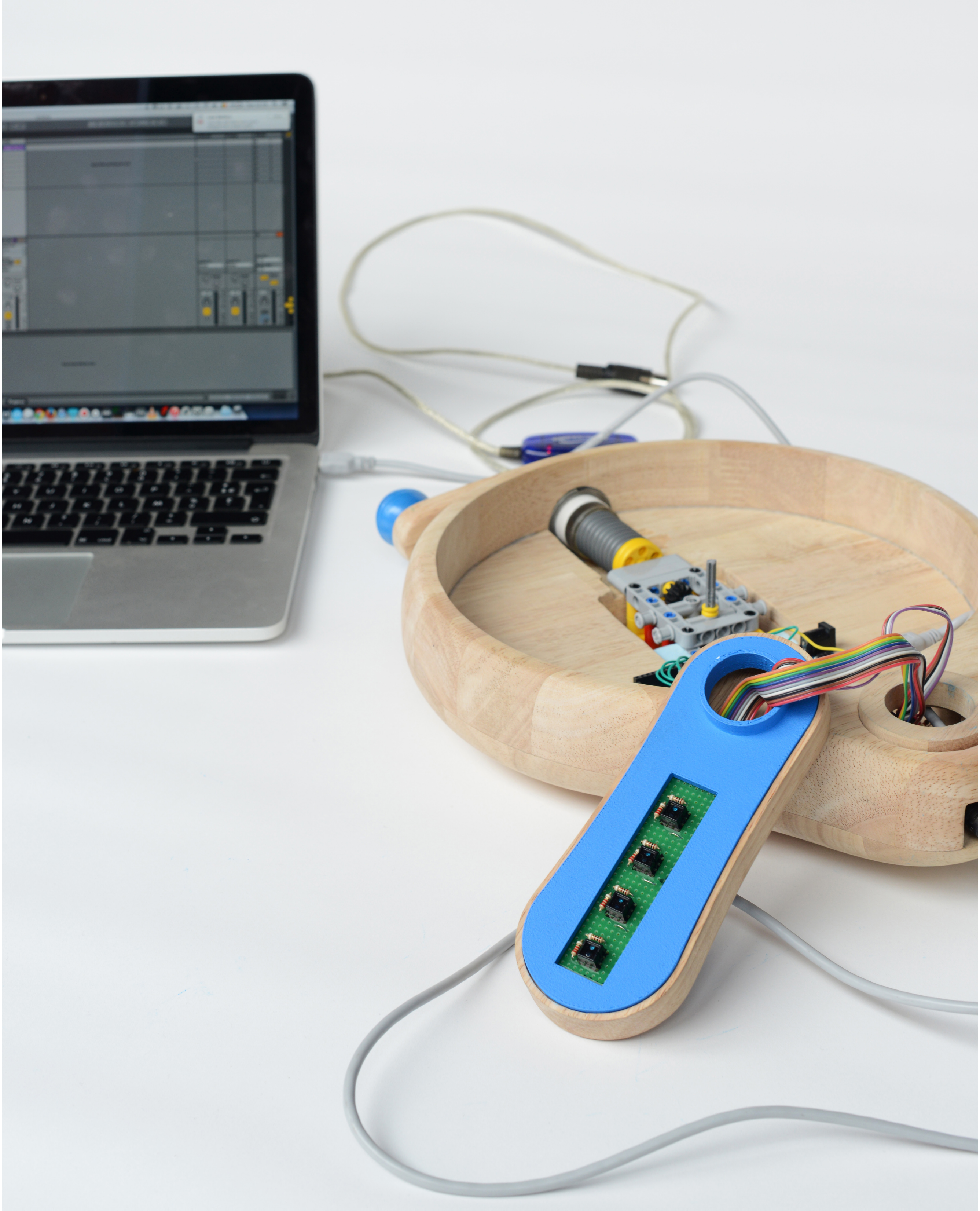

Figure 14 Inside of the final token-based sequencer prototype including the mechanical parts and electronics.

3.5 Experiment one: iteration three

Prototype development

A final high-fidelity prototype was constructed as a demonstrator model in order to make a more compelling interaction (see Figure 15). The interaction and form semantics of the design were further improved. Compared to the previous prototypes, more effort is invested in the detailed design and in the selection of the materials.

The turntable is enclosed in a double-curved housing made of rubber wood. The housing exists of two Computer Numerical Control (CNC) cut parts that are glued together. A reduction gear box (see Figure 14) was included inside the prototype, underneath the centre of the turntable. This gear box was built with LEGO Technic parts and is included to reduce the turntable's velocity. 3D printed LEGO compatible parts to connect the lever to the gear box were developed. The lever was moved to the side to ensure a good visibility of the turntable. A smaller reading unit was located above the turntable to detect the white, coin-shaped tokens on the turntable's surface.

Moreover, additional infrared sensors were included at the top half of the reading unit. These additional sensors are able to detect and interpret the coloured, ring-shaped tokens. These coloured, ring-shaped tokens physically represent different sounds and notes. They are used to select one sound for each row. Since the prototype is connected to the Ableton live library via the MIDI cable, the audio samples for the tokens can be easily changed. The Arduino UNO was replaced with an Arduino MEGA microcontroller to have enough Analog input pins available for the additional infrared sensors.

Description of the prototype

The final prototype demonstrates an example of a musical children's toy with a token-based TUI. The elements of a digital step sequencer are embodied in physical objects. The prototype enables a more intuitive and direct interaction with otherwise complex, abstract musical concepts. The prototype consists of two types of tokens (see Figure 15). The shape and colour of the token reveals its function, as well as how it should be used. The white, coin-shaped tokens are used to trigger notes and enable to physically construct musical patterns or beats. These tokens naturally fit into the turntable's looping rows. The coloured, ring-

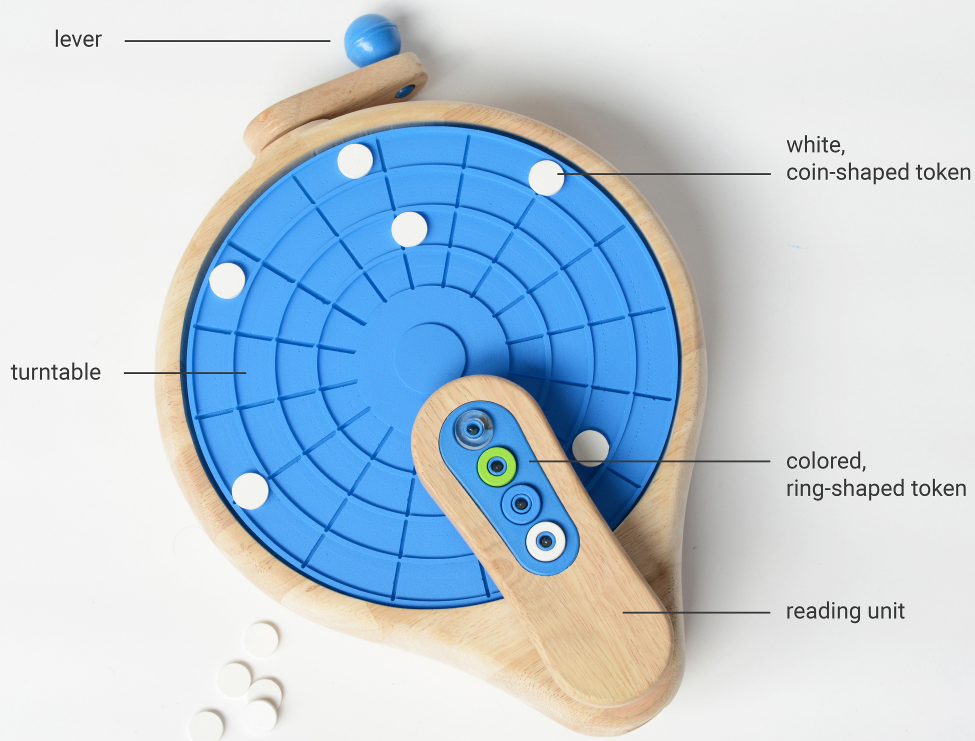

Figure 15 Presentation of the final token-based sequencer prototype and its components.

shaped tokens embody a different function. These tokens physically represent audio samples and are used to select a sound for each looping row. These tokens naturally fit into the ring-shaped slots in the reading unit. The tokens enable children to create and play beats in a playful and intuitive way. Other elements of the prototype further enrich the physical play experience of the prototype. To rotate the turntable, one has to use the lever on the side, instead of simply pressing a button to start the beat. Furthermore, the prototype should be controlled with both hands and is designed to fit in a child's lap (see Figure 16). The prototype allows for a much more intimate experience than a digital step sequencer on a computer.

Figure 16 A picture of a child playing with the token-based sequencer prototype.

Interaction scenario

The prototype consists of one main module with turntable and separate tokens. There are two types of tokens: white, coin-shaped tokens and coloured, ring-shaped tokens. The main module is placed on one's lap (see Figure 17a). By placing the coloured, ring-shaped tokens in the slots in the reading unit, one can select a sound for each looping row (see Figure 17b). The example below includes four different ring-shaped tokens (transparent, green, white, and blue). Each colour represents a different sound or note. By placing the white, coin-shaped tokens in the turntable's looping rows, one can create a musical pattern or beat (see Figure 17c,d). By turning the lever, the turntable starts rotating (see Figure 17e). Consequently, the white, coin-shaped tokens on the turntable are detected when they move under the reading unit. This causes the LED in the reading unit to blink, while the corresponding note is triggered (see Figure 17f).

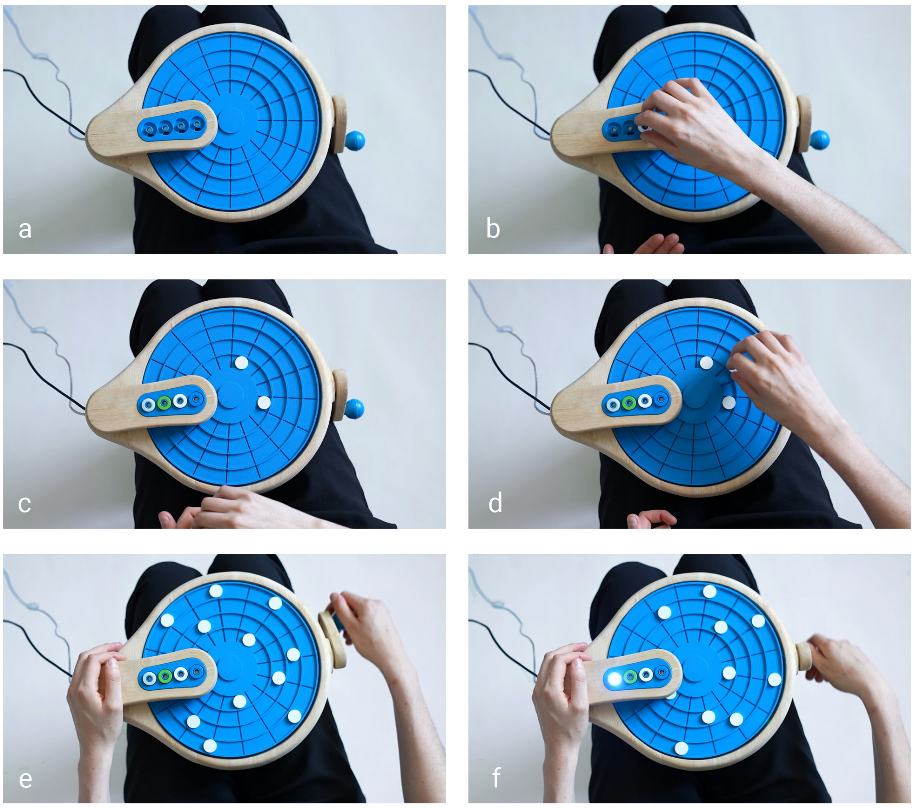

Figure 17 Presentation of the interaction scenario of the final token-based sequencer prototype.

3.6 Discussion: lead-up to the research program

Experiment one is presented as a precedent design project which precedes the research program. First and foremost experiment one is a design project and not a research project. Despite this, the precedent design project is included as one of the experiments, since it explores and demonstrates a new stance on token-based interaction and by doing so it enabled the formulation of the initial research program. It is not presented as a separate project because it clearly fits within the program which it helped to form.

It may seem odd that experiment one is conducted before having some idea of the research program. However, as argued by Redström (2017) the research program does not necessarily has to precede experimentation.

"As I argue later, this is true also in the case of relations between design programs and their experiments; the idea that programs precede experimentation evident in the opening anecdote is simply not correct, and overall the relationship between program and experiment is much more complex and dynamic. Indeed, what is important about the program from a design theory point of view is not that it precedes or governs experimentation but that it constitutes a definition of what designing is at a level of abstraction that experiments as such do not address....

we can say that while the order of things might differ, there is something about how the program offers a particular perspective on the experiment even when the experimentation initially preceded the formation of a program. Thus we might well end up in a situation where an experiment that was conducted long before the given program was articulated can still become an experiment within that program by being brought into it and seen through the lens of the program's worldview."

Still, one would expect the research program to be explained after and not before the experiment. This is not done in this case as by describing the program already in chapter two, before the presentation of experiment one, the reader receives information which is essential to understand the underlying ideas behind experiment one.

As discussed, the research program's initial stance on token-based interaction goes beyond the representational view put forward by Ishii and his colleagues. Van Dijk, Moussette, Kuenen, and Hummels (2013) have offered critique on Ishii's vision in which a tangible object is primarily an external representation of a digitally stored piece of information. In early tangible interaction physical objects are used essentially to represent digital information. According to van Dijk (2013, 2018) such token-based TUIs do not utilize the opportunities of manipulating physical form through bodily action, nor do they recognize the social situatedness of embodied interaction and therefore they are not truly embodied. Or in other words, these token-based TUIs do not fully capture the notion of embodiment as presented by Dourish (2001).

Despite the influence of Ishii's work, experiment one explores and presents a more 'embodied' kind of token-based interaction. Namely, the tokens in the token-based sequencer prototype are more than physical tags or storage media. The tokens are active components of the toy and stimulate embodied activity. The music produced with the tokens depends not only on the information which is stored on them, but also depends on how these tokens are arranged on the turntable, and the direction and speed of the movement with which the child rotates the lever.

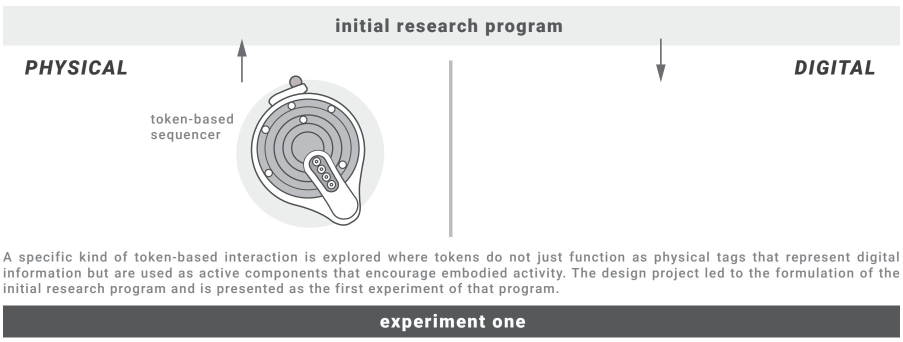

Figure 18 Evolution of the RtD process and research program.

Next to its influence on the formation of the research program, experiment one also sets a basis for the subsequent experiments (see Figure 18). In experiment two an adaptation of the token-based sequencer prototype is developed. Experiment two does not continue with the token-based sequencer prototype since the musical and interaction possibilities of the prototype are too limited. The prototype can only support 16 step beats. Longer beats or children's melodies are not supported. Furthermore, the interaction of the prototype is fully developed to reach a final, high-fidelity prototype. The extension possibilities that the prototype offers are too limited and may yield only detailed improvements. Other interaction possibilities may be more easily explored in different designs.

[10] *Similar designs are found online. Beat Blox is a graduation project of Per Holmquist from Beckmans College of Design in Sweden and was published online in September 2014 (CreativeApplications.Net, 2014). Another similar design called Orbita has been launched recently in 2021 by Playtronica (Playtronica, 2021). The token-based sequencer prototype was designed before these other designs were available online. The final results was presented as a graduation project in June 2014.*

Chapter four: Investigating a token-based interaction perspective

Part of the results presented in chapter four are based on the paper Van Camp, Van Campenhout, & De Bruyne, 2018 and the paper Van Camp et al., 2018.

4.1 Introduction

An adaptation of the token-based sequencer prototype designed in experiment one is designed in experiment two and experiment three in order to further refine my initial stance on token-based interaction and to explore new interaction possibilities. This chapter reports on the iterative design process of the digital toy train prototype. Iterative prototypes of a digital toy train with a token-based TUI are designed in two experiments. In these experiments comparative user evaluations are carried out with children aged five and six to evaluate the developed prototypes. These experiments enable the further investigation of a token-based interaction perspective in the context of children's toys and to assess children's preferences. Furthermore, the results demonstrate the usefulness of a This-or-That and Laddering method within an iterative design process.

The context of the case study was provided by a research project in collaboration with the manufacturer of a Flemish construction toy brand named CLICS (CLICS, n.d.). This two-year research project was a natural continuation of the MSc project which preceded this PhD research (see chapter three). This two-year research project is not considered fundamental research, but was aimed at applying the concepts of tangible and token-based interaction to an existing construction toy for innovation purposes.

4.2 Iterative design study

The iterative design study is organized around two experiments. Each experiment starts with a design phase followed by an evaluation of the designed prototype(s), analysis of the data from the user evaluations, and the formulation of new interaction possibilities. The main goal of the experiments is to assess children's preferences by measuring what type of interaction is preferred and why. The results do not provide conclusive evidence regarding the benefits of tangibility for children, but enabled the development of design recommendations for subsequent prototypes. Empirical methods for user evaluation are used to guide RtD as an iterative process.

Experiment two

In experiment two a first prototype of a digital toy train with a token-based TUI is designed. Comparative user evaluations with 34 children aged five and six were carried out to compare the prototype to two established commercial systems: a traditional toy train construction set from LEGO DUPLO, and a toy train game on a tablet called TuneTrain. Analysis of the data collected from the user studies enabled to evaluate children's preferences and to identify the desirable qualities of the systems tested. Furthermore, the results helped to formulate design recommendations to improve the interaction of the prototype.

Experiment three

After experiment two, two improved versions of the digital toy train prototype are designed and compared to each other. One version of the digital toy train prototype includes an extra set of tokens with animal sounds. The other version of the digital toy train prototype includes a separate graphical application which supports additional sound options. Comparative user evaluations with 44 children aged five and six are carried out to compare both versions of the prototype. The comparative user evaluations enabled to determine which version is most preferred and helped to identify the desirable qualities of each version.

Empirical methods for user evaluation

A This-or-That method (Zaman, Vanden Abeele, & De Grooff, 2013) was used to determine preference for the systems tested and a Laddering method (Vanden Abeele, Zaman, & De Grooff, 2012) was used to gain insight into the reasons for preference.

The empirical methods are used within comparative user evaluations that are carried out with children aged five and six. First, user-ready prototypes of a digital toy train with a token-based TUI are designed. These prototypes are then compared to existing toys or to different versions of the same prototype. All tests were conducted with one participant at a time. For the comparative user evaluations the participant was asked to play with each of the systems tested.

A This-or-That interview was conducted at the end of each user test. This-or-That is a comparison scale, which is considered to be a cognitively undemanding questioning technique, suitable for young children (Sim & Horton, 2012; Zaman, Vanden Abeele, & De Grooff, 2013). The participant was asked “Which of the systems tested was most fun?”. The participant could communicate their preference or indicate the preferred system simply by pointing. To determine preference for the systems tested, a ranking order was constructed with the results from the This-or-That questions.

After the This-or-That interview a Laddering interview technique was used to determine the reasons for preference. The participant was asked to explain the reason(s) for choosing one of the systems tested. To interpret the data collected from the Laddering interview, further data treatment is required. In the Laddering data treatment, the results from the interviews are transcribed into meaningful chains between the system’s attributes, consequences and values. These chains of attributes, consequences and values are also referred to as ladders (Vanden Abeele, Zaman, & De Grooff, 2012). In this study, every ladder links to the terminal value of fun, this was taken from the example of the study of Vanden Abeele, Zaman, and De Grooff (2012). It is important to note that, next to the data from an individual interview, the observations from the user study, plus the patterns of answers for all the different interviews, helped to interpret the participant’s responses and form ladders. In the Laddering data treatment only the answers related to the interaction with the systems tested were taken into account for constructing the ladders. Other reasons for preference were not considered relevant. For example, in experiment two, four of the 34 participants explained they preferred the game on a tablet because they have an iPad at home and one participant stated to like the digital toy train because her mother plays the piano. Many children gave irrelevant responses to the questions because they have a very short attention span or because they are too young to express their preferences verbally or even to crystallize them clearly. In most of these cases the responses are restricted to: "I do not know". Such responses are not useful to further improve the interaction of the prototype and were not used to form ladders.

Table 1 shows an example of how the transcriptions of the responses of a participant are transformed into a ladder.

Later the constructed ladders enabled the development of design recommendations for subsequent prototype.

Table 1 Example of a Laddering data treatment workflow.

This-or-That interview	
Facilitator	"Which of the three toys you just played, do you think is most fun?"
Participant #7	"This one." The participant points to the game on a tablet.
Laddering interview	
Facilitator	"And why do you like this one?"
Participant #7	"Because you can make songs like this." The participant makes the line-drawing movement with her finger.
Results after Laddering data treatment	
Attribute	Multi-touch display
Consequence	The system provides continuous graphical and audio output, when moving the finger across the display surface.
Value	Fun

4.3 Experiment two: design phase

Concept design

In experiment two, a prototype of a digital toy train with a token-based TUI is designed. This prototype is an adaptation of the token-based sequencer prototype designed in experiment one. Similar to the token-based sequencer concept, a concept of a musical children's toy that uses tokens to physically represent notes and sounds is designed. However, the digital toy train offers a different kind of interaction with tokens, and provides more musical and interaction possibilities than the token-based sequencer prototype.

In the digital toy train prototype the reader is not fixed, but moves along a path corresponding to the length of the created melody (see Figure 19). The adapted concept is designed to resemble a toy train so that the tokens can be placed into the toy train track. The electronic reading system is integrated in the toy train vehicle. Additional features such as other construction pieces (e.g., bridges, switch tracks), other types of vehicles (e.g., motorized vehicle) can expand the interaction possibilities of the prototype.

Just as in the token-based sequencer prototype, the tokens can be read and interpreted by an electronic reading system in order to play a rhythmic sequence of sounds. However, compared to the token-based sequencer prototype, the tokens are not placed on a turntable to create 16 step beats, but instead they are placed into the toy train track in a linear arrangement to create single note melodies (without chords). These melodies are not limited to 16 steps, but instead longer train track constructions can be build that can hold longer sequences of tokens in order to create longer children's melodies.

Furthermore, the digital toy train prototype only supports one type of tokens, whereas the token-based sequencer prototype works with two different types of tokens: one type of tokens to select the sounds for the different looping rows and one type of tokens to trigger the notes. The tokens in the token-based sequencer prototype are more generic, and abstract. In the first prototype of a digital toy train every token represents one sound. The sound associated to a token is represented by the physical features of the token, by its colour and by the icon on the top.

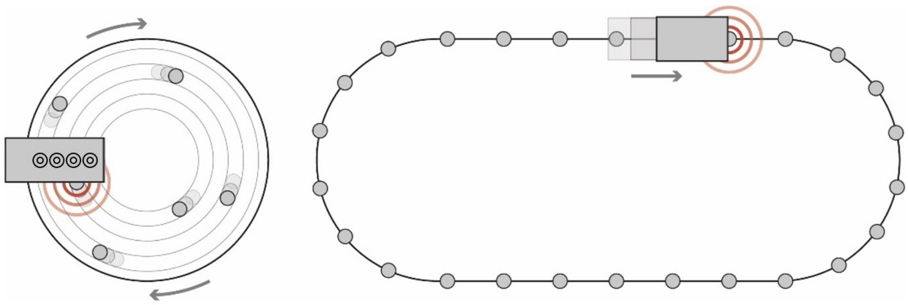

Figure 19 The illustration shows how the concept evolved between experiment one and experiment two. Left: token-based sequencer concept. Right: digital toy train concept. Both are concepts of musical children's toys that include an electronic reading system which can read and interpret tokens. Both concepts offer different musical and interaction possibilities.

Prototype development

For developing the prototype, building blocks from an existing construction toy are used. Using an established system has the advantage that it may facilitate the prototyping process. The system used is the CLICS construction set for children between 3 and 12 years (CLICS, n.d.). CLICS is a single-block system that consists of polypropylene square shaped blocks with hinge joints. Female joints are connected to male joints to build 3D constructions. The tokens and sections of train track are made compatible with the CLICS system. All hardware components were modelled in Solidworks. Computer Aided Design (CAD) files of these models were used for 3D printing the different parts. To identify the tokens 13.56MHz RFID stickers and an RFID RC522 reader were used. The compact Arduino Nano board was chosen to fit inside the toy train vehicle. The SparkFun bluetooth Mate Gold transmitter and receiver were used to wirelessly send data to a software application, written in Processing, running on the computer, to play the notes represented by the tokens.

Description of the prototype

With the prototype of a digital toy train, children aged five and six can construct and play children's melodies in a physical and playful way. The interaction with the prototype does not feel PC-like. All digital functionalities are embodied in physical objects or tokens. For addressing the toy's functions, children do not need to navigate menu structures or press combinations of buttons. Instead, children can build a melody by grasping, placing and shifting physical building blocks or tokens. Compared to graphical content displayed on a tablet, these tokens fit in the child's hands and facilitate a wider repertoire of physical actions. Furthermore, the aim was to make the prototype look less digital and more like a traditional toy train by embedding all electronic elements in the physical building blocks.

Overview of the different parts and interaction scenario

The interaction with the prototype is based on the use of tokens. Next to the tokens (Figure 20a), the prototype consists of construction pieces (Figure 20b), and a reader, a toy train vehicle constructed from CLICS blocks (Figure 20c). The construction pieces – curved and straight sections of train track – do not contain digital elements. They act as traditional building blocks and can be mechanically connected to each other to build a railway (Figure 20d). There is a slot in each section for placing the tokens (Figure 20e). The tokens are square shaped objects and represent musical notes. In total, the prototype consists of ten tokens, representing the following notes: three 1/8 notes: A#3, C4, D4, five 1/4 notes: A#3, A3, C3, F3, G3, and two 1/2 notes: C4, F3. All the different sounds can be retrieved from this link (Soundcloud, n.d.). The notes were selected to allow the construction of simple children's melodies such as "Frère Jacques". Icons on top of the tokens help the children to distinguish the different notes. RFID tags are used to electronically store digital information in the tokens. The data stored in the tokens can be accessed with the electronic reading system embedded in the reader. By placing the reader on the train track and manually pushing it forward along the constructed railway (Figure 20f), the tokens in the train track are identified and the notes stored on them are played.

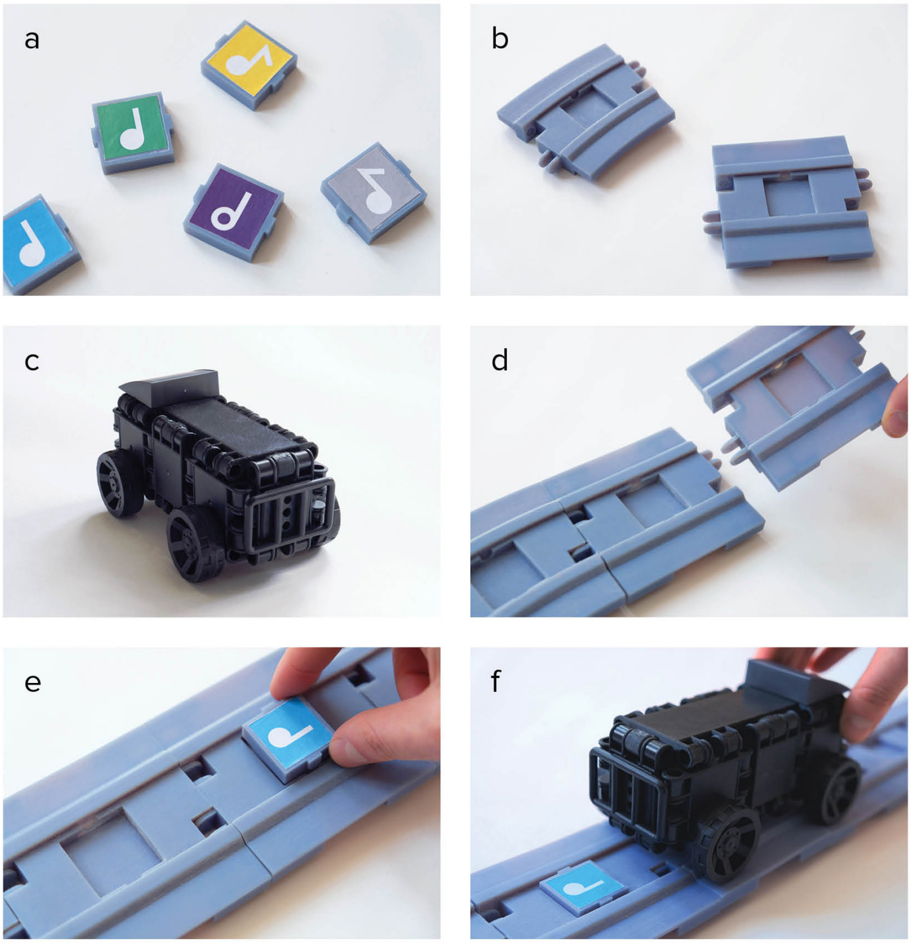

Figure 20 Prototype of a digital toy train, iteration one. Overview of the different parts and interaction scenario.

4.4 Experiment two: user evaluation

Systems tested

A comparative user evaluation was carried out with the following systems:

A traditional toy train construction set from LEGO DUPLO [11] (LEGO, n.d.-a). With this construction set children aged two to five years can build a track for a motorized train. The traditional toy train contains no digital elements. Instead, the LEGO system focuses on physical play with traditional building blocks.

A digital toy train prototype with a token-based TUI. With the prototype children aged five and six can physically construct and play children's melodies with the use of tokens.

A toy train game on a tablet available in Apple's iTunes store. In the TuneTrain game (Apple App Store, n.d.) children aged four and older can create and edit melodies using a line-drawing function. The game features a GUI which allows the children to select subgames and sounds and other additional features.

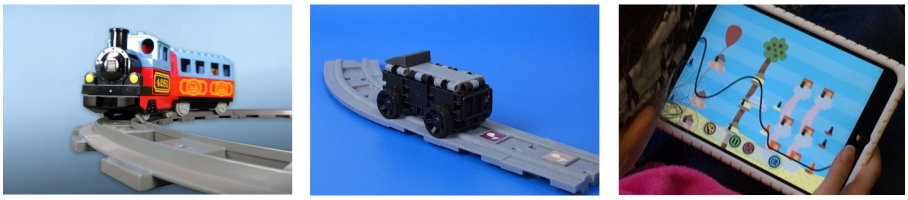

Figure 21 The systems tested in experiment two. Left: a traditional toy train from LEGO DUPLO. Centre: the digital toy train prototype with a token-based TUI. Right: a toy train game on a tablet called TuneTrain.

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[11] *In 2018 LEGO launched a new version of their DUPLO train with tokens (LEGO, n.d.-b). This system from LEGO DUPLO led to the development of a new LEGO Education line (Ibid). This system is similar to the digital toy train prototype in that it includes coloured tokens that can be placed into the train track to be read and interpreted by the toy train vehicle. However, this specific version with tokens was not yet on the market when the digital toy train prototype was designed and evaluated, which took place in 2015 and 2016 respectively. The results of experiment two were presented at the Applied Human Factors and Ergonomics Conference held during July 17 – 21, 2017 in Los Angeles, USA and are published in Van Camp, Van Campenhout, & De Bruyne, 2018. A first sketch of the digital toy train was included in the project proposal approved in 2015 by the Flemish Agency for Innovation and Entrepreneurship, also known as VLAIO (project number 150303). The digital toy train prototype is an adaptation of the token-based sequencer prototype and was in no way inspired by the LEGO DUPLO design.*

Participants

The user tests were carried out with children aged five and six attending early formal education. Two pre-primary schools participated in the study. Three different classes participated in the experiment. In total, 34 children (17 boys, 17 girls) participated. All necessary approvals – parental and ethical approval – were obtained prior to conducting comparative user studies with children. The children had the opportunity not to participate in this study or to stop their participation in the study at any time. Figure 22 below shows two pictures taken during the user evaluation.

Figure 22 Pictures taken during the user evaluation. Left: participant playing with the game on a tablet. Right: participant playing with the traditional toy train.

Test setup

All user tests were conducted in classrooms that were provided by the participating schools. The three systems were placed in separate areas of the room. A video camera was placed on a tripod in the centre of the room. All tests were conducted with one participant at a time. The participants played with each system for a maximum duration of ten minutes. One facilitator was present to coordinate the test. The facilitator intervened only to ask the participant to move to the next system or in case any clarification was needed.

Data acquisition

After the participant played with each system, the facilitator asked the participant some questions to determine which system is preferred and why. During the This-or-That interview the participants were asked: “Which of the three toys was most fun?” Subsequently, the participants were asked: “Which of the two remaining toys was most fun?” A ranking order was constructed with the results from the This-or-That questions, which counts three points for the first choice, two points for the second choice, and one point for the third choice. A nonparametric repeated-measures Friedman test (determined using IBM SPSS Statistics V24 software) was used to check if the measured results are significant. A Wilcoxon Signed Rank test (determined using IBM SPSS Statistics V24 software) was used to evaluate within-group pairwise differences. In the Laddering interview the participants were asked to explain the reasons for their preference. Afterwards, in the Laddering data treatment, relevant ladders were constructed with the data from all the 34 interviews.

4.5 Experiment two: results of the user evaluation

Results This-or-That method

All of the 34 participants were able to give a first, second, and third choice. The traditional toy train scored 56 points. The digital toy train prototype scored 67 points. The game on a tablet scored 81 points. The mean score is 68. The scores given by each of the participants are found in Appendix one.

The Friedman test showed that the measured results are significant, $\chi 2F(2) = 9.235$, $p = .010$. The results of the Wilcoxon Signed Rank test varied for each pair with A = traditional toy train, B = digital toy train, C = game on a tablet:

B - A:	T = 367,	z = -1.232,	p = .218
C - B:	T = 409,	z = -2.086,	p = .037
C - A:	T = 446,	z = -2.618,	p = .009

The statistical output obtained from SPSS is found in Appendix two.

Table 2 Results This-or-That method experiment two. The table shows how many participants have chosen the system tested as a first, second, and third choice, together with the total score for each of the systems tested.

Systems Tested		Traditional toy train	Digital toy train	Game on a tablet
First choice	(3)	9	8	17
Second choice	(2)	4	17	13
Third choice	(1)	21	9	4
Total score		**56**	**67**	**81**
Difference from mean score		-12	-1	+13

Results Laddering method

Five of the 34 participants were not able to explain the reasons for their preference. Eight of the 34 participants gave irrelevant responses to the Laddering questions, leaving 21 valid respondents. In total 21 relevant ladders were constructed out of the 34 interviews. These 21 ladders are grouped into five types of ladders. The ladders formed for each of the participants are found in Appendix one.

Table 3 Results after Laddering data treatment. Schematic overview of the constructed ladders in experiment two.

Systems tested	Ladder	Attribute	Consequence	Value	Number of ladders
Traditional toy train	1	Motorized train	Watch the train as it moves over the train track	Fun	7
Digital toy train	2	Tokens	Create something yourself	Fun	3
	3	Tokens	Surprise effect	Fun	3
Game on a tablet	4	Digital database	Many musical possibilities and subgames	Fun	5
	5	Multi-touch display	Provide continuous graphical and audio output	Fun	3

The results of the This-or-That method show that the toy train game on a tablet, is most preferred among the participants. Laddering reveals two main qualities of the game on a tablet.

1. First, a Laddering method revealed that the most attractive quality of the system resides in its versatility. In total, five participants indicated that they like the variety of sounds and games you can play. This quality can be attributed to the system's broad digital database that supports multiple subgames and musical possibilities.

2. Second, three participants liked moving their finger across the tablet's display. Some children were more specific and explained that the tablet makes many sounds when doing that. When moving your finger across the multi-touch display, different sound samples graphically appear and are being played. This causes the game on a tablet to be more stimulating

than the digital toy train prototype with a token-based TUI or the LEGO DUPLO train. This stimulating effect seems to be greatly appreciated by young children. This was also observed during the user tests. In general, the participants appeared to be less bored when they were playing with the game on a tablet than when playing with the digital toy train or the traditional toy train.

The prototype of a digital toy train with a token-based TUI ranks second, but has valuable qualities. A Laddering method helped to reveal these qualities.

1. First, the Laddering results suggest that performing physical actions with tokens makes users more aware of their actions. Namely, three children stated that they preferred the digital toy train because it enables them to create their own melody. However, also in the game on a tablet the goal is to create a melody. Yet none of the participants gave this as a reason for their preference. An explanation for this can be that compared to graphical content, physical objects are persistent and remain physically present in the environment. Consequently, one's actions affect the environment and leave visible traces. This may have caused the children to feel that they actually created something themselves, a feeling of being part of the process, a feeling of being in control. Similar conclusions have been reported in other studies (Hassenzahl & Klapperich, 2014; Kankainen, 2016; Trammell, 2010; Van Campenhout, 2016).

2. Second, the prototype of a digital toy train looks like a traditional toy train with no digital functionality or interactive capabilities. By embedding RFID tags into the tokens, the tokens are made interactive. However, these tags are not visible to the user. This may explain why some children acted surprised when the reader sensed and responded to the tokens in the train track. Three children stated they prefer the digital toy train because the toy train vehicle can make sounds, while none of the participants mentioned this about the game on a tablet, as they might expect this for a game on a tablet.

And finally, Laddering revealed that the traditional toy train from LEGO DUPLO is mainly preferred for its motorized train. This can be confirmed by the observations. The children really enjoyed watching the motorized train as it moved over the train track.

Design recommendations

The constructed ladders contributed to the derivation of three design recommendations for a subsequent prototype. The design recommendations are based on the three ladders that were constructed for the traditional toy train and game on a tablet. The design recommendations are ranked in terms of the number of ladders counted.

1. A first recommendation is to add a motorized vehicle to the prototype. (see Table 3: ladder one, traditional toy train, number of ladders = seven)

2. A second recommendation is to increase the number of sounds that can be played by the prototype. The current prototype only supports ten different sounds. (see Table 3: ladder four, game on a tablet, number of ladders = five)

3. A third recommendation is to make the prototype more stimulating by adding real-time graphical and/or audio feedback. (see Table 3: ladder five, game on a tablet, number of ladders = three)

4.6 Conclusion of experiment two

Experiment two fits within the initial research program and builds further on the results of experiment one. A first prototype of a digital toy train with a token-based TUI is designed. The digital toy train prototype with a token-based TUI is an adaptation of the token-based sequencer prototype designed in experiment one (see Figure 23). The digital toy train prototype is based on the same kind of token-based interaction, but offers more musical and interaction possibilities than the token-based sequencer prototype. Hence, the digital toy train prototype exposes additional interaction possibilities of the research program.

Moreover, by evaluating the prototype the research program is put to the test. The user evaluation enabled to get a better understanding of the strengths of the specific kind of token-based interaction proposed in the research program. The digital toy train prototype with a token-based TUI is opposed and compared to two established systems with contrasting interaction styles: a traditional toy train and a toy train game on a tablet. A comparative user evaluation was carried out with 34 children aged five and six. The results of this comparative user evaluation show that the toy train game on a tablet is most preferred due to its broad digital database with many different sounds and games and its ability to provide stimulating output. The prototype of a digital toy train ranks second, but has valuable qualities. Namely, tokens may allow moments of surprise and playing with these tokens left some of the participants feeling they had created their own melody. The traditional toy train ranks last in the evaluation and was mostly chosen for its motorized vehicle.

Next to identifying the desirable qualities of the systems tested, Laddering also helped to derive three design recommendations to improve the interaction of the prototype. Based on these three design recommendations two improved versions of the digital toy train prototype are designed in experiment three. One version includes a graphical application and thus moves away from the research program's initial aim for full tangibility in children's toys. The other version is a fully tangible system with extra tokens.

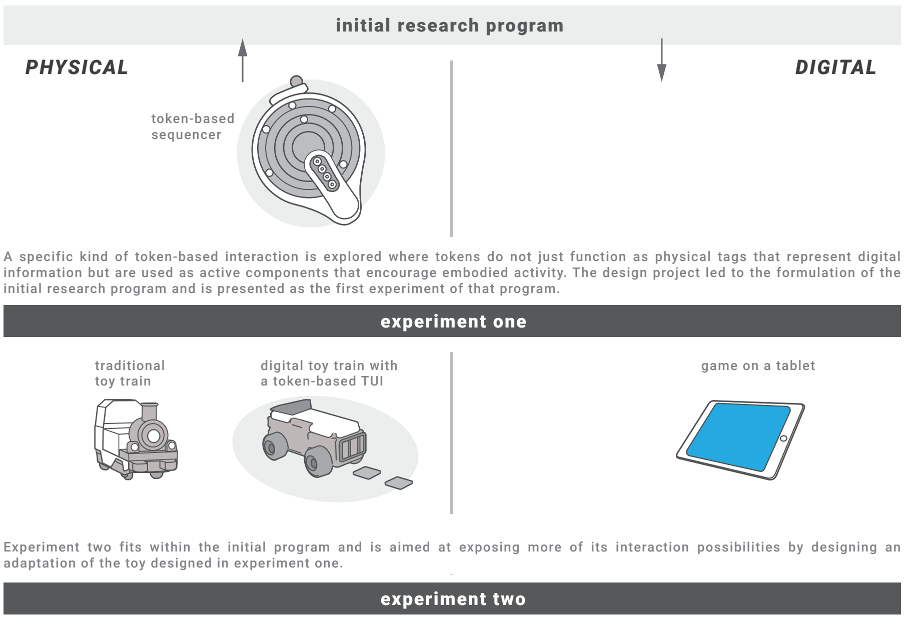

Figure 23 Evolution of the RtD process and research program.

4.7 Experiment three: design phase

Concept design

The interaction of the digital toy train prototype was further improved based on the design recommendations made in experiment two. The design recommendations helped to make the design decisions described below. It is important to note that these design decisions are not the only ones which could have been derived from the design recommendations, as different designers might have interpreted the data differently or would have prioritized different research goals.

1. First, a motorized vehicle is added to the prototype. The toy vehicle with reader remains non-motorized, but can be attached to the motorized vehicle. This way the children can choose to manually push the reader forward, or to attach it to the motorized vehicle to play the constructed melody.

2. Second, the number of sounds that are supported by the prototype are increased to make the prototype more versatile. The prototype developed in experiment two supports ten piano sounds. An animal theme set including ten more sounds of different animals was added to the prototype. Two different strategies were followed to include these additional animal sounds. The additional animal sounds can either be embodied in tokens, or a graphical application which supports a digital database with both the piano theme and animal theme can be added to the prototype. Both of the strategies were pursued which resulted in two different versions of the same prototype. One version of the digital toy train prototype with extra tokens and one version of the digital toy train prototype with graphical application.

3. Third, adding a graphical application to the prototype does not only make the prototype more versatile, but also makes the prototype more stimulating than the digital toy train prototype designed in experiment two. This complies with the third design recommendation.

Prototype development

Instead of reusing the building blocks from the CLICS system, specific construction pieces were designed, so that more attention could be paid to the interaction and form semantics of the prototype. Additional effort is invested in the detailed design and in the exploration of alternative shapes and materials. The result is

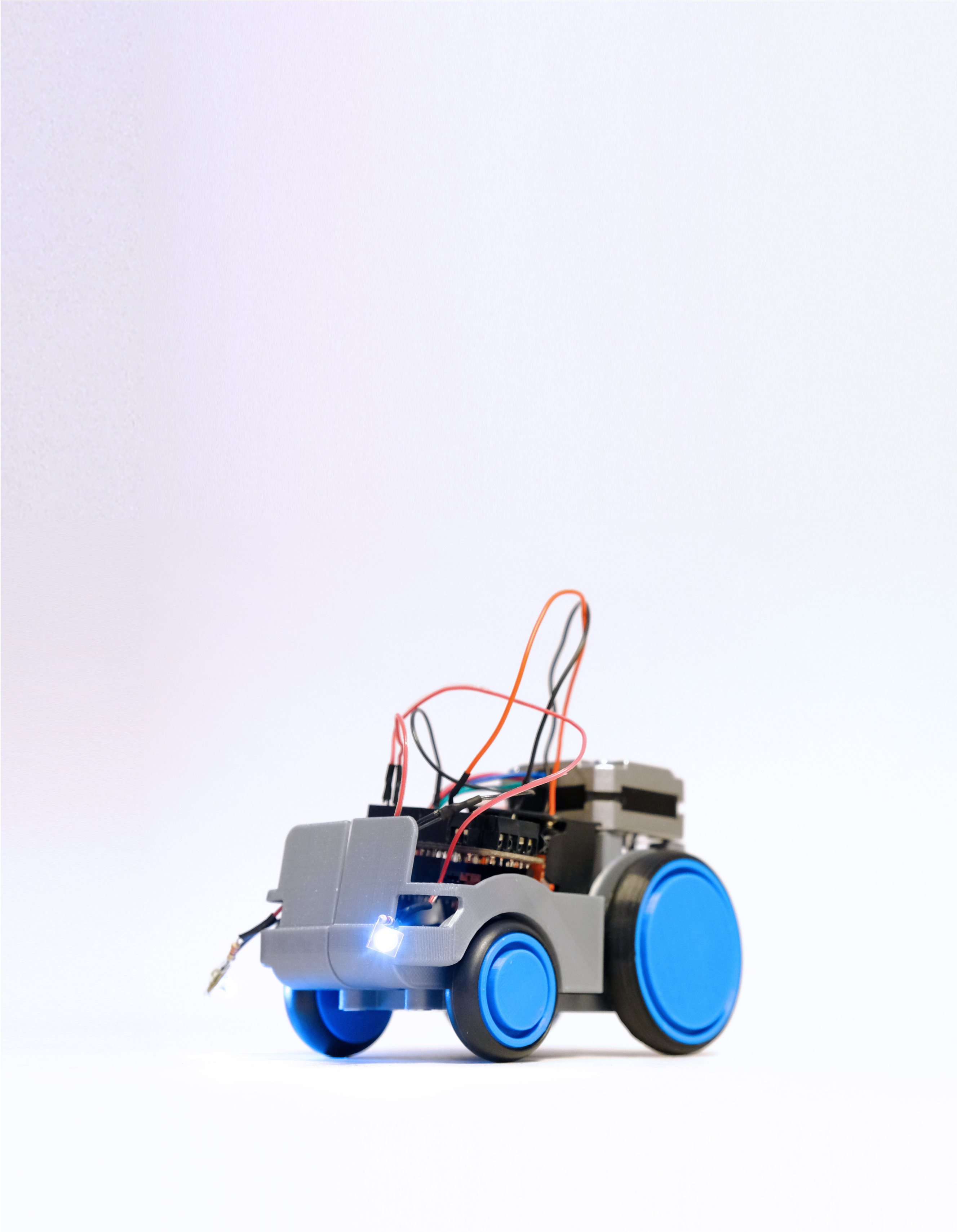

Figure 24 Inside of the motorized vehicle with stepper motor.

a higher-fidelity and more robust prototype which has an overall better finish and detailing. The dimensions are based on those of the former prototype. All parts were modelled in Solidworks. Parts of the designed toy vehicles and tokens were printed with Prusa MK2 printers. The additional tokens, with integrated icons of animals, were printed with the Prusa MK2 Multi Material upgrade that can print simultaneously in four colours. All these parts were printed in PLA. For the sections of train track, a more simple connection mechanism was chosen, which is common for many toy train tracks and requires less physical effort to build a railway compared to the CLICS system. All sections of train track were cut on a 3-axis CNC milling machine. For these sections of train track beech hardwood was used. Beech is commonly used in toys since it is not toxic. The tokens consist of 13.56 MHz RFID stickers, which can be read and interpreted by the electronic reading system. The motorized vehicle consists of a nearly silent stepper motor (17HS08-1004S) (see Figure 24). A differential from LEGO Technic is included in the motorized vehicle to ensure a constant velocity for not disrupting the rhythm of the played melody. The graphical application was developed using the Processing programming language and displays a selection menu for the two musical themes.

Description of the prototype

The prototype's overall function remained unchanged. The interaction of the prototype was improved based on the design recommendations from experiment two. A motorized vehicle is added to the prototype. Moreover, an animal theme set with ten more sounds is added to the prototype. Two versions of the same prototype were designed. In one version the additional animal sounds set is embodied in a set of tokens with animal icons. In the other version a graphical application is added to the prototype that displays the two themes: piano sounds and animal sounds. Next to improving the interaction of the prototype, more time was dedicated to the design and the selection of materials. Wooden sections of train track are designed to preserve the traditional look and feel of the prototype (see Figure 25).

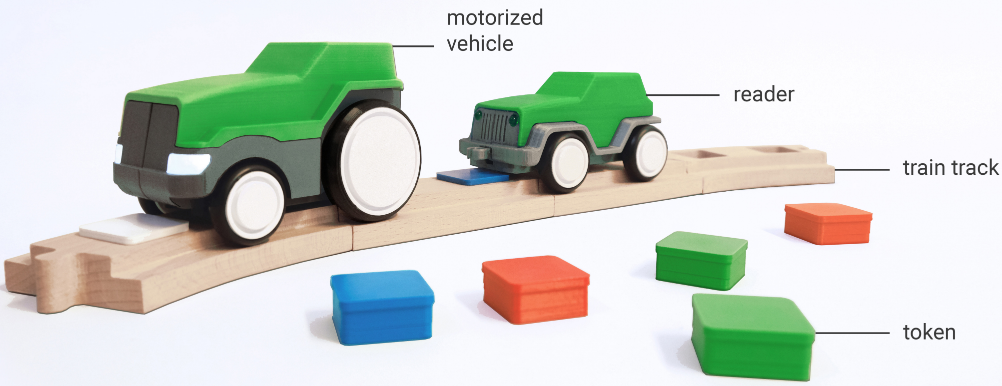

Figure 25 Presentation of the digital toy train prototype and its components.

Overview of the different parts

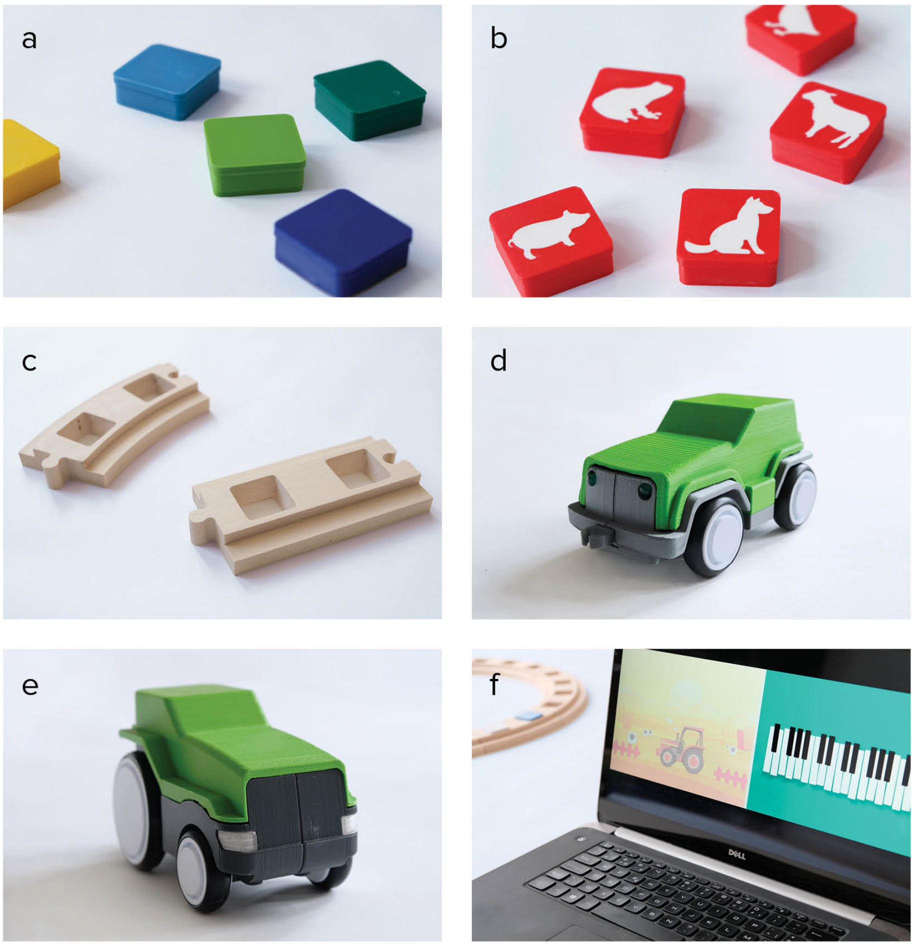

Figure 26 Prototype of a digital toy train, iteration two. Overview of the different parts.

Interaction scenario

To build a railway the wooden sections of train track (Figure 26c) are mechanically connected to each other (Figure 27a). The prototype consists of a basic set with ten coloured tokens (Figure 26a) and an extra set with ten different animal sounds (Figure 26b). In the basic set, each colour represents a different note. These notes are the same as the ones used in the previous prototype. The animal theme set uses icons to make the information stored in the tokens visible. All the different sounds can be retrieved from this link (Soundcloud, n.d.). The tokens are placed into the slots of the sections of train track (Figure 27b). The tokens can be read and interpreted by the reader (Figure 26d). Children can choose to manually push the reader forward (Figure 27c), or to attach it to the motorized vehicle (Figure 27d), in order to play the constructed melody.

The other version of the prototype only consists of one set of tokens. These generic coloured tokens (Figure 26a) are combined with a graphical application (Figure 26f) that runs on a separate computer. The information stored in the coloured tokens can be changed by selecting a different musical theme in the graphical application. A musical theme can be selected simply by clicking on the corresponding image (an illustration of a piano or an illustration of a farm with animals) with the computer mouse.

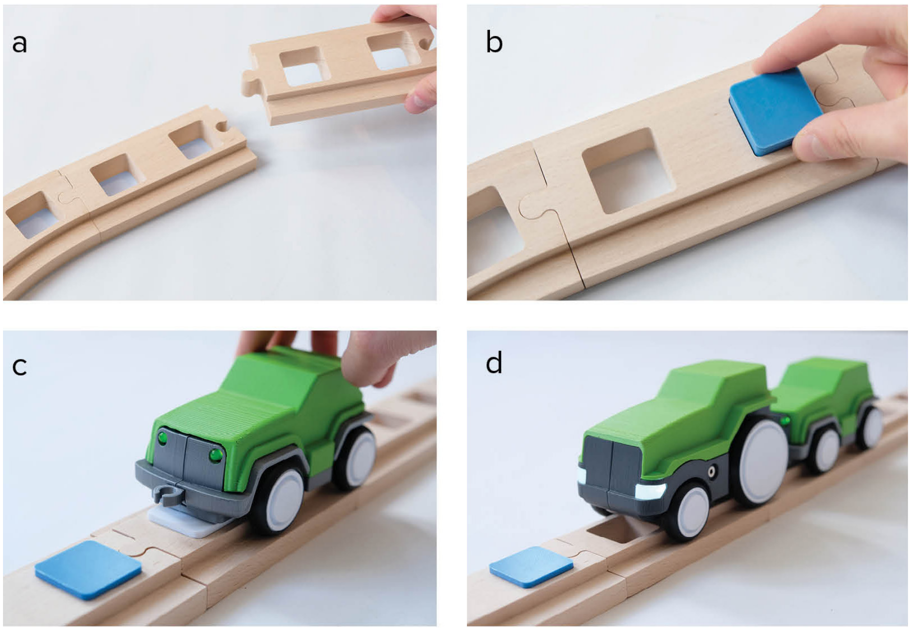

Figure 27 Prototype of a digital toy train, iteration two. Interaction scenario.

4.8 Experiment three: user evaluation

Systems tested

A comparative user evaluation was carried out with the following systems:

In the first version of the prototype an additional set of tokens with animal sounds is added to the prototype to increase its versatility.

In the second version of the prototype a graphical application is added to the prototype to increase its versatility and to make the prototype more stimulating. The graphical application displays a simple selection menu, which enables the allocation of two musical themes (piano notes and animal sounds) to the generic tokens.

Participants

The user tests were carried out with children aged five and six attending early formal education. Two pre-primary schools participated in the study. Three different classes participated in the experiment. In total, 44 children (22 boys, 22 girls) participated. All necessary approvals – parental and ethical approval – were obtained prior to conducting comparative user evaluation studies with children. The children had the opportunity not to participate in this study or to stop their participation in the study at any time.

Test setup

All user tests were conducted in classrooms that were provided by the participating schools. The prototype was placed central in the room, with a video camera in front of the prototype. The test setup consisted of the physical prototype and a separate laptop, which was used to interpret and play the different sounds and to run the graphical application for selecting the musical themes. All tests were conducted with one participant at a time. The participants played with each system for a maximum duration of ten minutes. During the tests one facilitator was present. The facilitator intervened only to ask the participant to move to the next system or in case any clarification was needed. A picture taken during the user evaluation is shown in Figure 28.

Figure 28 Picture taken during the user evaluation.

Data acquisition

As in experiment two, a This-or-That and a Laddering method was used to determine which system is preferred and why. In contrast to experiment two, two similar systems with distinct attributes were evaluated instead of comparing three clearly distinguishable systems.

After the user tests, the participants were asked how they preferred to select the sounds in the prototype (using the computer or using the extra set of tokens). This way a ranking order was derived. The systems were ranked, according to an index which counts two points for the first choice, and one point for the second choice. A Wilcoxon Signed Rank test (determined using IBM SPSS Statistics V26) was used to check if the measured results are significant. Subsequently, the participants were asked to explain their preference for one of the two systems tested. These interviews were then transformed into ladders.

Additionally, the participants were asked if they preferred using the manual or motorized option. The results of experiment two suggest a preference for using a motorized vehicle instead of manually pushing the reader forward. The validity of this recommendation is verified to evaluate the usefulness of a This-or-That and a Laddering method within an iterative design process.

4.9 Experiment three: results of the user evaluation

Results This-or-That method

43 of the 44 participants were able to select a first choice. One participant was not able to rank the systems tested. The prototype with extra tokens scored 74 points. The prototype with graphical application scored 55 points. The scores given by each of the participants are found in Appendix three.

The mean score is 65 points. The Wilcoxon Signed Rank test showed that the measured results are significant, $T = 682$, $z = -2.897$, $p = .004$. The statistical output obtained from SPSS is found in Appendix four.

Table 4 Results This-or-That method experiment three. The table shows how many participants have chosen the system tested as a first and second choice, together with the total score for each of the systems tested.

Systems Tested		**Digital toy train with extra tokens**	**Digital toy train with graphical application**
First choice	(2)	31	12
Second choice	(1)	12	31
Total score		**74**	**55**
Difference from mean score		+9	-10

Additionally the participants were asked if they preferred using the manual or motorized vehicle. 33 of the 44 participants stated they preferred the motorized option over manually pushing the reader forward. The responses for each of the participants are found in Appendix three. Both versions of the digital toy train prototype include a motorized vehicle. So the motorized vehicle did not influence preference for one of the two versions of the prototype. These responses should be seen separately from the This-or-That responses summarised in Table 4.

Results Laddering method

Seven of the 44 participants were not able to explain the reasons for their preference. 21 of the 44 participants gave irrelevant responses to the Laddering questions, leaving 16 valid respondents. In total 17 relevant ladders were constructed out of the 44 interviews, as one participant constructed two ladders. All the 17 ladders are grouped into the following five types of ladders (see Table 5). The ladders formed for each of the participants are found in Appendix three.

Table 5 Results after Laddering data treatment. Schematic overview of the constructed ladders in experiment three.

Systems tested	Ladder	Attribute	Consequence	Value	Number of ladders
Digital toy train with extra tokens	1	Tokens	One token per sound, having a physical representation of each sound	Fun	5
	2	Tokens	No need to go to the computer, you can directly play the melody	Fun	4
	3	Tokens	Surprise effect	Fun	3
	4	Tokens	Physical movements are perceived as more pleasurable	Fun	3
Digital toy train with graphical application	5	Graphical application	Easy to switch between musical themes, efficient	Fun	2
					17

The results of the This-or-That method show that the digital toy train with extra tokens is most preferred among the participants. Laddering revealed four qualities of the version with extra tokens.

1. First, tokens enable to have a physical representation of each sound. This has multiple advantages. Two participants stated that with the generic tokens it is not clear which sound goes with which token. When asking them why they prefer choosing the sounds with the extra tokens they answered: "Because then you can choose for yourself which sound you want to hear, and with the computer you do not know which sound you choose." They

prefer using specific tokens over generic ones. These specific tokens can include icons to indicate what data is stored inside the tokens. Furthermore, two participants stated that when playing with the digital toy train with extra set of tokens, you do not have to choose one of the musical themes, instead you can use both musical themes at the same time. Finally, one participant liked that each sound has its own block.

2. Second, four participants explained that they disliked having to go to the computer for selecting a different musical theme and therefore preferred the digital toy train with extra tokens. With the tokens you can immediately start playing the melody. They answered: "Because I can directly drive with the car" and "Because otherwise you have to go to the computer every time and click on that".

3. Third, three participants liked that the tokens can trigger sounds. They seemed to act surprised when the generated sounds corresponded with the icons on the tokens (e.g., the token with the horse icon triggers a neighing sound).

4. And finally, Laddering revealed that the participants perceived the placing of the tokens as a pleasurable activity. Namely, three participants explained that they liked to play with the tokens, and to place them into the train track.

Considerably fewer ladders were constructed for the digital toy train with graphical application. However, Laddering revealed that the graphical application provided a more efficient solution for selecting the sounds compared to using an extra set of tokens. Namely, the graphical application enabled the participants to easily change the musical theme of the melody without having to change the tokens. One participant answered: "I did not like these (points to the tokens with animal sounds) because you have to take them in and out every time".

Design recommendations

No additional design recommendations were formed to further improve the interaction of the prototype. In experiment three the systems tested only differ from each other at a product-attribute level. The research benefit of comparing even smaller differences in interaction is limited. Moreover, fewer ladders were formed in experiment three than in experiment two (21 ladders were formed for 34 participants in experiment two, compared to 17 ladders for 44 participants in experiment three). Obviously it is easier for children to describe their overall judgement of clearly distinct systems, than to indicate preference on attribute level. The latter requires a more detailed answer, which might be cognitively too demanding for younger age groups. Thus, the systems to be tested in a subsequent experiment might be too much alike for the children to differentiate and to complete valid Laddering interviews. Furthermore, some of the suggested design recommendations are better explored through different designs. The digital toy train prototype was originally designed as an example of a digital toy with a token-based TUI. Simply adding a separate graphical application to the prototype, might not lead to the desired effect. Zaman, Vanden Abeele, Markopoulos, and Marshall (2012) warn researchers to be careful in comparing TUIs and GUIs. They state that in studies where the product in question was originally designed as a TUI, the GUI alternative runs the risk of becoming no more than a damaged counterpart.

4.10 Conclusion of experiment three

Based on the design recommendations from experiment two, additional sounds and a motorized vehicle were added to the prototype to improve the interaction of the prototype. Two versions of the same prototype are designed. The digital toy train with extra tokens is a fully tangible system and includes two sets of tokens. The digital toy train with graphical application only includes one set of tokens, but a graphical application is added to the prototype to select additional sounds. A comparative user evaluation was carried out with 44 children aged five and six to compare both versions to each other. The results of this comparative user evaluation show that the digital toy train with extra tokens is preferred. Laddering revealed four desirable qualities of using tokens. Namely tokens may lead to experiencing moments of surprise, enable the user to directly play the melody without having to go to the computer, are pleasurable to use, and can provide physical representations for sounds. And finally, the digital toy train with graphical application ranks last in the evaluation but proves to be more efficient than the digital toy train with extra tokens.

4.11 Discussion: striving for an advantageous combination

This chapter investigates a token-based interaction perspective in the context of children's toys. Iterative prototypes of a digital toy train with a token-based TUI are designed and evaluated in two experiments.

In experiment two, a first prototype of a digital toy train is designed. Experiment two enabled to explore additional interaction possibilities of the specific kind of token-based interaction proposed in the research program. The digital toy train prototype with a token-based TUI designed in experiment two was compared to a traditional toy train and a toy train game on a tablet. The results of experiment two show that the game on a tablet is most preferred. When it comes to versatility, and stimulation the game on a tablet outperforms the digital toy train. However, the digital toy train with a token-based TUI ranks second and has other beneficial qualities. The results of experiment two show that playing with tokens may allow moments of surprise, and makes children more conscious of their actions.

In experiment three, two improved versions of the digital toy train prototype are designed. One version keeps the initial stance. This version is a fully tangible system which includes an extra set of tokens. The other version includes a separate graphical application instead of extra tokens. This separate, graphical application is added to the digital toy train to make the prototype more stimulating and versatile.

The decision to add a graphical application to the prototype is based on the fact that TUIs have their limitations. TUIs are said to be "limited by their single-purpose static physical form" (Siu et al., 2017). Physical objects or tokens are not ideal means to fully capture the possibilities of the digital world. Physical objects are rigid and static in comparison to digital information that is flexible and dynamic. Therefore, physical objects cannot fully embody the versatile and adaptive characteristics of digital information. This is not a new insight obtained from the experiments, it has already been described in 2007 by Poupyrev, Nashida, and Okabe. They explain that "indeed, one of the most attractive properties of the digital world is malleability: digital objects are easy to create, modify, replicate, and distribute. Physical objects on the other hand are rigid and static, which limits their utility in TUIs". In order to overcome the limitations of the physical world they suggest that "if we could dynamically change physical properties of TUI elements: their shape, texture, position, speed of motion, and so on, the design vocabulary of TUIs would expand tremendously".

There are many researchers that have advanced the field further by making the physical properties of TUIs more dynamic and flexible so that they can change shape.

For example, Frens (2006) designed prototypes of digital cameras to investigate how the action possibilities of digital products can be extended through shape changes (see Figure 29). His final prototype can take on different shapes. Each shape reflects a specific product state and affords specific action possibilities. When switching to a new state, new action possibilities appear, while the non-relevant ones are hidden. Frens successfully employed the concept of shape-change in a concrete and viable product example.

Also, Vallgårda has contributed to the effort to make the physical more dynamic and flexible. Vallgårda's work builds further on the concept of temporal gestalt as described by Hällnas and Redström (2002). They explain that computers execute digital processes and that these processes are temporal and that therefore temporal gestalt should be a central form element of all computational things (Ibid). Or in other words, designers should not only design the spatial properties of computational things, but will also have to deal with how their spatial form changes over time and thus temporal gestalt will come to play an important role. Vallgårda further complements and refines the concept of temporal gestalt in the design of computational things as she proposes this trinity of forms as a framework for interaction design (Vallgårda, 2014). According to Vallgårda, there are three key form elements in interaction design: temporal form, physical form, and the interaction gestalt. She explains how interaction design practice is about forming a whole through an ongoing negotiation between the three form elements (Ibid). In her designs Vallgårda puts this framework into practice. Her designs are related but further away from industrial design. Instead, she has explored this framework through several interactive installations (e.g., PLANKS (see Figure 29) (Vallgårda, 2008)) or through digital materials and textiles that can change shape (e.g., (Vallgårda, Winther, Mørch, & Vizer, 2015)). Vallgårda's notion of trinity of temporal form, physical form, and interaction gestalt has been explored extensively in the field of shape-changing interfaces. According to Sturdee and Alexander (2018), "Vallgårda creates a baseline for the new type of interaction design necessary for shape-changing interfaces, in which temporality meets the physical and the interactive possibilities of such devices". Shape-changing interfaces are said to advance TUIs (Rasmussen, Pedersen, Petersen, & Hornbæk, 2012). Early TUIs could not reflect changes in digital information and could not be manipulated except by moving them. Shape-changing interfaces are a type of TUIs that use shape-change to enhance the interactive capabilities of TUIs (Kwak, Hornbæk, Markopoulos, & Bruns Alonso, 2014). These shape-changing interfaces have evolved beyond mere self-actuated physical objects to create these sort of hybrid or composite materials with computational abilities (Parkes & Ishii, 2010; Vallgårda & Redström, 2007).

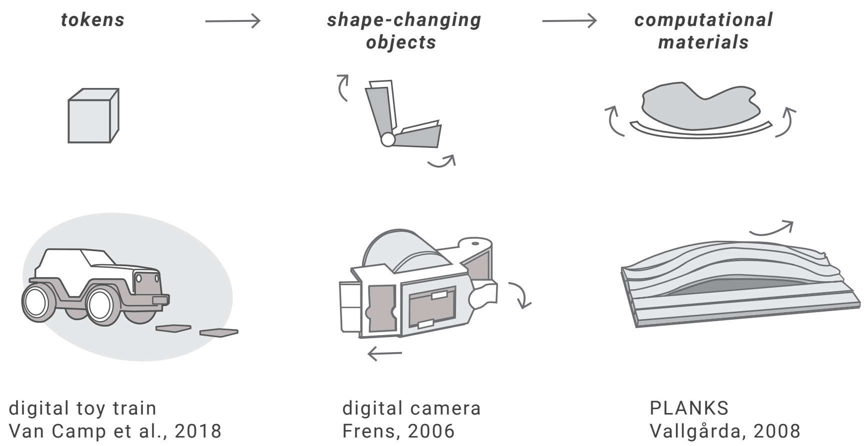

Figure 29 This figure shows three types of tangibles. Tokens are static, physical objects, they do not offer the same possibilities or flexibility as shape-changing objects or computational materials. They are restricted by their static, physical form.

Shape-changing interfaces illustrate a much more advanced understanding of tangible interaction than the one employed in experiment one to experiment three. The first experiments of this thesis rely on token-based interaction which is an early and basic form of tangible interaction. The interaction possibilities of the prototypes developed in these experiments do not go beyond those of rigid, static physical objects. Obviously, the digital toy train prototype has its limitations. More tokens, vehicles, or construction pieces can be added to the prototype to extend the interaction possibilities, but this has little research value.

The research program could remain closer to its initial standpoint and aim for full tangibility in children's toys by investigating how the interaction possibilities of TUIs can be extended by applying the concept of shape-change. However, a different research direction was chosen. Namely, the results from the Laddering interview showed that token-based TUIs and GUIs are preferred for very different reasons which are often inherently tied to essential features of the system tested. For example, GUIs are preferred because they can provide stimulating and appealing graphical output. This is something which simply cannot be achieved with a tangible toy. So instead of striving to continually improve and extend the possibilities of tangible children's toys in order to obtain a compelling alternative to games on a tablet, the research program starts to acknowledge that each of them has their own beneficial qualities and cannot simply be replaced by the other.

As such, from this point onwards, the research program no longer opposes children's toys and games on a tablet but aims to combine the beneficial qualities of each. Or in other words, the research program no longer strives to replace all graphically-displayed digital information with physical objects or tokens, but strives to search for an advantageous combination of both.

Experiment four aims to investigate how such an advantageous combination can be achieved and looks into the possibilities of hybrid interaction. Concretely, in experiment four a prototype of a programming toy with a HUI that combines a TUI and a GUI is designed. Experiment three already took a first step in this direction by adding a graphical application to the digital toy train prototype. However, experiment three did not reward this choice as the fully tangible digital toy train with extra tokens was chosen over the digital toy train with graphical application. The Laddering results show that adding a separate graphical application to the prototype is not preferred, as the participants repeatedly had to switch between the digital toy train and the graphical application running on a separate computer, which disrupted the interaction flow. The graphical application was treated as a separate element like it is often seen today in an app that accompanies a product such as a wireless bluetooth speaker which is controlled with an app on a smartphone. Despite the negative evaluation of the digital toy train prototype with graphical application designed in experiment three, experiment four recognizes the added value of a GUI, but searches for a better balance between the TUI and the GUI.

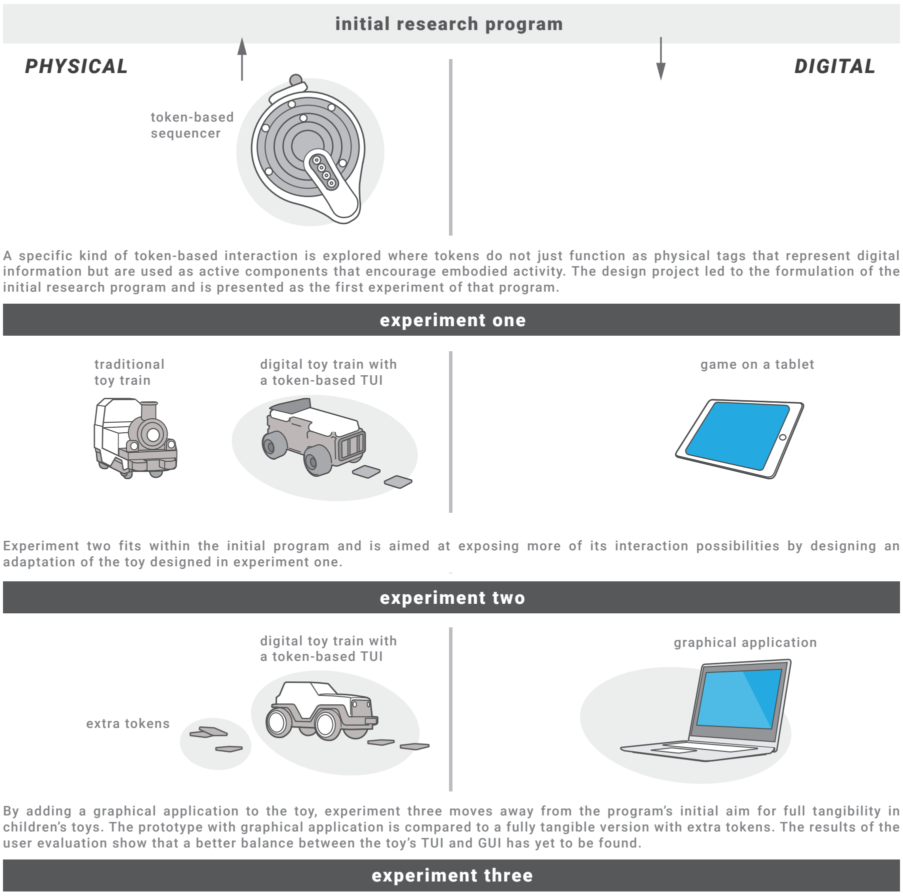

Figure 30 Evolution of the RtD process and research program.

Chapter five: Investigating a hybrid interaction perspective

5.1 Introduction

This chapter forms a bridge between the previous chapters, that investigate a token-based interaction perspective and prioritize physical representations of digital information, and the next chapters, where graphical content is given a more important role to play. Experiment three took a first step in attempting to combine the benefits of TUIs and the versatile possibilities of GUIs, but the right balance between the TUI and the GUI was not found. In experiment four a prototype of a programming toy with a HUI that combines a TUI and a GUI is designed in order to strike a better balance. Other examples of children's toys with a HUI are discussed and compared to the prototype.

5.2 Definition of Hybrid User Interfaces

HUI is a generic term which has been applied to a variety of interfaces [12]. The term 'HUI' refers to a single digital system that consists of two or more equivalent interfaces [13] (Horn, Crouser, & Bers, 2012). These interfaces are equivalent as they are used within the same system and follow the same interaction mechanism. They are distinct since they support different interaction styles. It is said that by combining such equivalent or complementary interfaces in one system, HUIs take advantage of the strong points of each (Feiner & Shamash, 1991).

In the context of children's toys, the term 'HUI' is often used to refer to the intersection of physical and digital, traditional toys and digital games (Tyni, Kultima, & Mäyrä, 2013). This thesis uses the definition provided by Strawhacker and Bers (2015): a HUI is an interface that consists of a TUI and a GUI, in which users can switch freely between physical and graphical input. Other studies that investigate HUIs in a context of children’s toys have also adopted this definition (Alderliesten et al., n.d.; Strawhacker, Sullivan, & Bers, 2013; Tsimplinas, Berki, Valtanen, & Sapounidis, 2019).

5.3 Experiment four: Fix the Shuttle

Presentation

Fix the Shuttle is the result of the MSc thesis of Cedric Lodewijckx, a second year master student Product Development at the University of Antwerp. I initiated and supervised this master project [14]. The result of the master project is Fix the Shuttle, a programming toy with a HUI for children aged 7 to 12. The toy consists of coding cards that represent different programming actions (left, right, function, condition, loop,...), a control board, a gameboard with physical building blocks, a reflector, and a graphical application on the tablet (see Figure 31). The player needs to solve programming exercises with the cards. The formed coding sequences tell Bubba a bluetooth controlled miniature robot who is seeking its way out of a maze, where to go (see Figure 33). The toy offers multiple challenges. For each challenge the player has to build a specific maze configuration. By solving the challenges children learn programming skills in a playful manner.

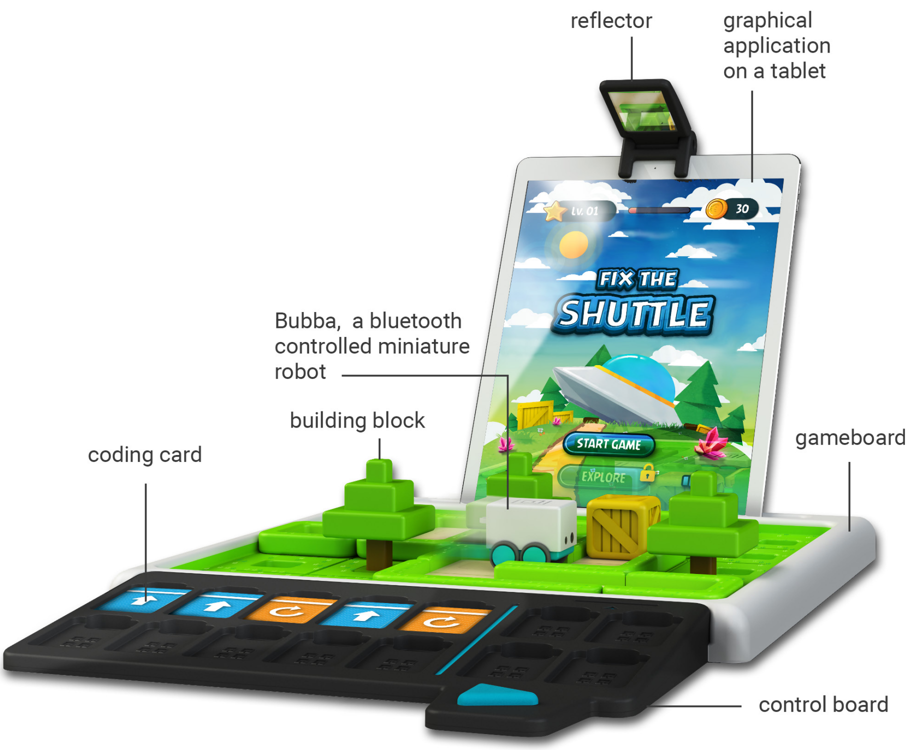

Figure 31 Presentation of the Fix the Shuttle prototype and its components.

Description of the interaction

The interaction scenario is shown in Figure 32. At the start, the gameboard is clear and only the graphical application on the tablet is used (Figure 32a). First the child chooses the difficulty level in the graphical application on the tablet, he/she can choose between four difficulty levels: starter, junior, expert, and wizard (Figure 32b). After selecting a difficulty level, the graphical application loads an animated tutorial to teach the child a new concept or control which will be used in the following challenge round (Figure 32c). After finishing the tutorial, a ground plan of the maze is showed on the tablet's display (Figure 32d). The child is asked to reconstruct the maze with the physical blocks. The physical blocks, the trees, roads, Bubba the robot, and the wooden crate should be arranged on

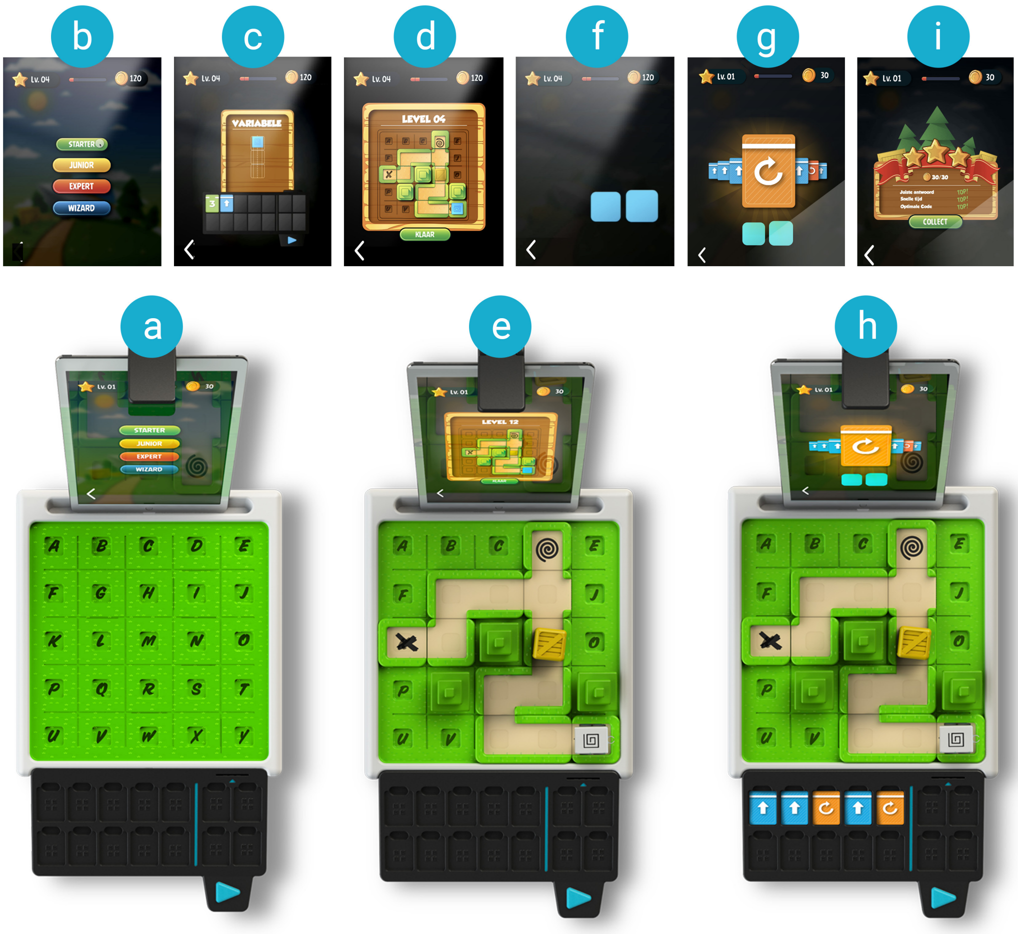

Figure 32 Overview of the different steps in the interaction scenario of the Fix the Shuttle toy.

the gameboard so that their location corresponds to the maze displayed on the tablet's display (Figure 32e). Due to the reflector, the tablet's camera can track the location of the physical blocks. That the camera tracks and sees what is going on in front of the tablet is reflected in the form of eyes which move nervously over the tablet's display (Figure 32f). After building the maze, the child has to guide Bubba the robot to the end of the maze. This is done by forming the correct code. A code is constructed by placing the physical coding cards on the control board (Figure 32h). Once a code is constructed, the child can send the code to the graphical application by pressing on the blue button on the control board. The character displayed on the tablet's display goes over the code to check if the code is correct (Figure 32g). When the code is incorrect, the character will ask the child to revise the code. When the code is correct, the child receives a reward and can proceed to the next level (Figure 32i).

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[12] *For example, a HUI can refer to interfaces that combine multiple input and output devices such as a HUI used for radiological diagnosis that combines a zSpace stereoscopic display with 2D displays, and mouse and keyboard input (Mandalika et al., 2018); a HUI can also refer to interfaces that combine several interaction paradigms, e.g., a VR system that combines Windows Icons Menus Pointer (WIMP) and mid-air gestural interaction (Koller et al., 2020) or a chatbot that combines natural language interaction with GUI interaction (Androutsopoulou, Karacapilidis, Loukis, & Charalabidis, 2019).*

[13] *Horn, Crouser, and Bers (2012) use the term equivalent interfaces to refer to interfaces with distinct interaction styles that nonetheless share a common essential interaction metaphor. The idea is that designers will select an essential interaction metaphor to assist users in the transition between interaction styles. An example of an essential interaction metaphor is one of connecting interlocking blocks—this action represents the process of constructing syntactically correct computer programs. In the tangible system, these programming elements are real wooden blocks, and in the graphical system, they are pictures on a computer screen.*

[14] *The master project was linked to a proposed but not funded research project in collaboration with SmartGames (SmartGames, n.d.). The research project focused on exploring the potential of HUIs for Science, Technology, Engineering, and Mathematics (STEM) toys. The goal was to combine SmartGames' online and offline segments. SmartGames live offers an online alternative to the physical puzzles of SmartGames. However, both have not yet been combined in one toy.*

Figure 33 A picture of Bubba seeking its way out of the maze.

Prototype development

A non-functional prototype was created consisting of a CNC cut game- and control board and 3D printed robot, maze blocks, and reflector. All parts were painted to match the colours as shown in Figure 31. The coding cards were printed on cardboard. The elements of the prototype do not contain any electronics or microcontroller. The different physical objects of the prototype have to be moved manually in order to simulate the interaction scenario. An interactive prototype of the graphical application is designed in Flinto (Flinto, n.d.). This software enables the creation of a graphical application without having to know any program language.

Wizard of Oz user study

The developed prototype was used to conduct a Wizard of Oz user study. Wizard of Oz is a well-established method for simulating the functionality and user experience of future systems. Rather than developing a fully functional prototype, a human 'wizard' is used to mimic certain operations of the system to make the user believe the system is fully functional. Wizard of Oz is particularly useful in situations where extensive engineering effort would otherwise be needed to evaluate the designed system (Schlögl, Doherty, & Luz, 2015). The Wizard of Oz user study was carried out with children aged seven to nine. One primary school participated in the study. In total eight children participated. All tests were conducted with one participant at a time. The school was informed regarding the study and written consent was obtained. The children had the opportunity not to participate in this study or to stop their participation in the study at any time. All user tests were conducted in classrooms that were provided by the participating school. Two video cameras were used to record the user tests. The prototype was placed on a platform so that the facilitator could make Bubba the robot move with the help of a magnet. Furthermore, the facilitator had to navigate through the GUI, based on the actions of the user to simulate the behaviour of the application. The participants were asked to play the first seven levels (including the introductory levels) of the game. The facilitator did not give any additional information. Figure 34 shows a picture taken during the Wizard of Oz user study.

The result of the user evaluation are based on observations of the user tests and questions asked during these user tests. During the observations the facilitator paid attention to the usability of the three main components of the prototype (the control board, the game board, and the graphical application on the tablet). Each time a participant was not able to solve a puzzle, the facilitator asked questions and tried to understand what went wrong. Next to the usability the facilitator paid particular attention to the overall interaction and play experience. Unlike experiment two and experiment three, the results are not based on empirical methods, but rather on observations and interviews with the children during the user tests.

The results of the Wizard of Oz user study show that the game is initially complicated to figure out. Many participants experienced difficulties solving the first levels. The game consists of many different elements. At the start, it is not always clear when to use which element, some elements are confused with each other and not used in the correct order. For example, the participants often forgot to use the control board when forming the coding sequences. After playing more levels the participants started to understand how to use the interface. The results from the user observation are particularly useful since they show that it is difficult to find a good balance between the different elements of the toy. The results expose a potential pitfall. When the right balance is not found, combining multiple, distinct elements in one interface may lead to the development of confusing and complex solutions. A similar conclusion emerged from a study conducted by a group of international students which I supervised for their European Project Semester (EPS). The goal of their EPS project was to design a digital toy train with a HUI. The developed prototype is an adaptation of the digital toy train prototype designed in experiment three and is presented in Alonso Gil et al. (2018).

Figure 34 Picture taken during the Wizard of Oz user study.

5.4 Striking a balance

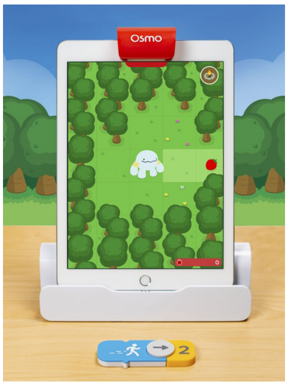
The aim of experiment four is to strike a balance between the toy's TUI and GUI. Compared to the digital toy train prototype with graphical application designed in experiment three, there is less distance between the TUI and the GUI of the Fix the Shuttle prototype. In the Fix the Shuttle prototype both the TUI and the GUI are located around the same gameboard. Another feature that brings them closer together is the reflector. By placing the reflector over the tablet's camera, the GUI can scan and respond to what is going on in the area in front of the tablet. This is reflected in the eyes displayed on the tablet's display that follow Bubba as he seeks a way out of the maze (see Figure 35). This interaction goes beyond simply bringing the TUI and GUI spatially closer together. The GUI seemingly becomes aware of its physical environment.

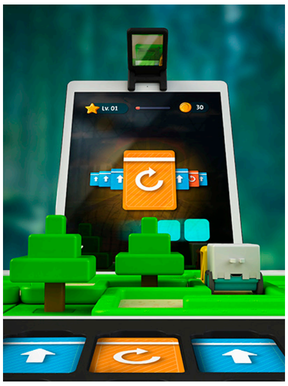
This is not seen in other similar programming toys with a HUI. The design of the Fix the Shuttle toy draws from the LEGO BOOST construction toy and the Osmo Coding Awbie toy. These two commercial toys offer the same functionality as the Fix the Shuttle toy. In all three toys the goal is to construct a code and to then upload the code to control a character or a robot. Table 6 describes for each of the toys how the TUI and the GUI are related to each other.

LEGO BOOST (LEGO, n.d.-c) lets children create robotics constructions with physical building blocks, motors, and sensors. In a separate graphical application displayed on a tablet, the child can construct coding scripts that can be uploaded to bring their creations to life. By pressing play in the graphical application, the robot starts executing the formed coding script. While the TUI and the GUI are co-dependent on each other, they are not used at the same time, nor do they co-operate in any way. The user actions are performed sequentially and separately in the TUI and the GUI.

Similar to the Fix the Shuttle toy, Osmo Coding Awbie (Osmo, n.d.) lets children use physical objects in the real world to interact with the digital world shown on the tablet. In the Osmo Coding Awbie toy, the coding functions are embodied in physical objects and a game character Awbie is displayed on the tablet's display. By solving the programming puzzles with the physical coding blocks, children can guide Awbie through a maze and can help him to find strawberries on his way. Compared to Bubba the robot, Awbie is an animated character displayed on the tablet's display and not a bluetooth controlled miniature robot. Furthermore, instead of making Awbie move through a physical maze, the maze is displayed on the tablet's display. Just as the Fix the Shuttle prototype, Osmo Coding Awbie comes with a reflector that is placed over the tablet's camera so that the tablet can track the location of the physical coding blocks. The GUI is aware of what is going on in front of the tablet, but there is no interaction between the TUI and the GUI.

Table 6 Comparison of the Fix the Shuttle toy to two commercial programming toys with a HUI that offer the same functionality. Left: LEGO BOOST. Center: Osmo Coding Awbie. Right: Fix the Shuttle. The table describes for each of the toys how the TUI and the GUI are related to each other.





LEGO BOOST	Osmo Coding Awbie	Fix the Shuttle
The TUI and the GUI are co-dependent on each other, but are not used at the same time, nor do they co-operate in any way. The user actions are performed sequentially and separately in the TUI and the GUI.	The GUI can track the location of the physical coding blocks to verify the solution. There is no further interaction between the TUI and the GUI.	The GUI is aware of what is going on in front of the tablet and can track the movement of Bubba. This is reflected in the eyes displayed on the tablet's display that follow Bubba as he seeks a way out of the maze.

Figure 35 The picture shows how the eyes on the tablet's display follow Bubba as he seeks his way out of the maze.

Other children's toys with a HUI strike a similar balance between the TUI and the GUI as the one demonstrated in the Fix the Shuttle prototype.

Disney Appmates (Heater, 2011) is an example of a children's toy with a HUI that strikes a balance between the toy's TUI and GUI. The toy consists of toy cars themed around Pixar's Cars and a game on a tablet. The small physical toy cars contain capacitive pads in a set order at the bottom of the cars. When the toy car is placed on the tablet, the app recognizes these pads and becomes active. By turning the physical car, the player can steer it and drive it over the race track displayed on the tablet's display. When driving the toy car across the display, the scenery races by. Headlights and different optional accessories appear on the display around the toy car as if they are really attached to it (see Figure 36). While playing, the graphical content displayed on the tablet's display are synchronized to the position and the movement of the toy car.

Figure 36 In the Disney Appmates toy headlights and different optional accessories such as wings appear on the tablet's display around the toy car as if they are really attached to it. Pictures courtesy of Disney Pixar.

The Nintendo labo kit (Nintendo, 2018) is another example of a children's toy with a HUI that strikes a balance between the toy's TUI and GUI. In the Nintendo labo kit the TUI and the GUI are closely attuned to one another. Children can create cardboard constructions in which a tablet is integrated. One of the constructions that can be built with the Nintendo labo kit is the Toy-Con house. The Toy-Con House cardboard construction is designed to hold a tablet so that the physical cardboard controls form a direct extension of the graphical content displayed on the tablet's display. The Toy-Con House comes with a game on a tablet that shows the interior of a customizable house full of mini games. By inserting assembled blocks into the openings in the Toy-Con House, one can interact with and play games with the inhabitants displayed on the tablet's display. Figure 37 shows how a crank handle can be used combinedly with the push block to whip a jump rope around and make a creature jump over it. The whipping of the jump rope displayed on the tablet's display happens simultaneously and is linked to the action of turning the crank handle.

Figure 37 Picture of the Nintendo labo Toy-Con House construction. The cardboard construction can hold a tablet. Cardboard controls are used to interact with the game character displayed on the tablet's display. In this picture, the player uses the crank handle to control the jump rope to make the displayed character jump over it. Picture courtesy of Nintendo.

The analysis of other children's toys with a HUI shows that in some cases the TUI and the GUI work together as one (e.g., Disney Appmates and Nintendo labo), whereas in other cases they act as separate entities (e.g., LEGO BOOST and Osmo Coding Awbie). Or, in other words, in some cases the TUI and the GUI are intertwined to a synchronous experience, whereas in others they take turns.

5.5 Discussion: close together but not united

Figure 38 gives an overview of how the RtD process has further evolved and shows how experiment four builds further on the previous experiments.

As discussed, in experiment two the game on a tablet was preferred over the prototype of a digital toy train with a token-based TUI. A graphical application was added to the digital toy train prototype designed in experiment three in order to combine the versatile and graphically-appealing interfaces of games on a tablet with the benefits of TUIs. However, this decision was not positively received by the children. The fully tangible digital toy train with extra tokens was preferred over the digital toy train with graphical application. This could be because the right balance between the toy's TUI and GUI was not found. The participants responded that they disliked having to go to the computer to use the graphical application and therefore preferred the fully tangible digital toy train with extra tokens.

In order to strike a better balance between the toy's TUI and GUI the research program is extended to look into the possibilities of hybrid interaction. In experiment four, a prototype of a programming toy with a HUI that combines a TUI and a GUI is designed. Compared to the digital toy train prototype with graphical application designed in experiment three, the TUI and the GUI of the Fix the Shuttle prototype are closer together. They are closer together not only spatially, but the TUI and the GUI also interact more closely with one another. Unlike the graphical application in the digital toy train prototype, the GUI is not detached from its physical environment, but instead responds to what is going on in the area in front of the tablet. Due to the reflector, the GUI 'sees' where the physical objects of the TUI are located. The tracking of the physical objects is displayed graphically in the form of eyes that are moving over the display's surface and attentively follow the child's actions and the movement of the physical objects. However, one can argue that the TUI and the GUI of the toy are indeed closer together, but not united. The Fix the Shuttle prototype is an assembly of separate, inter-related parts. These parts do not form one whole, but instead they belong to two different worlds and are separated by a border between them. This is well depicted in Figure 38 which clearly shows how the TUI lies on the left side of the border and belongs to the physical world, while the GUI lies on the right side of this border and belongs to the digital world. Experiment five builds further on experiment four and is aimed at blurring the border between them so that they can form one whole.

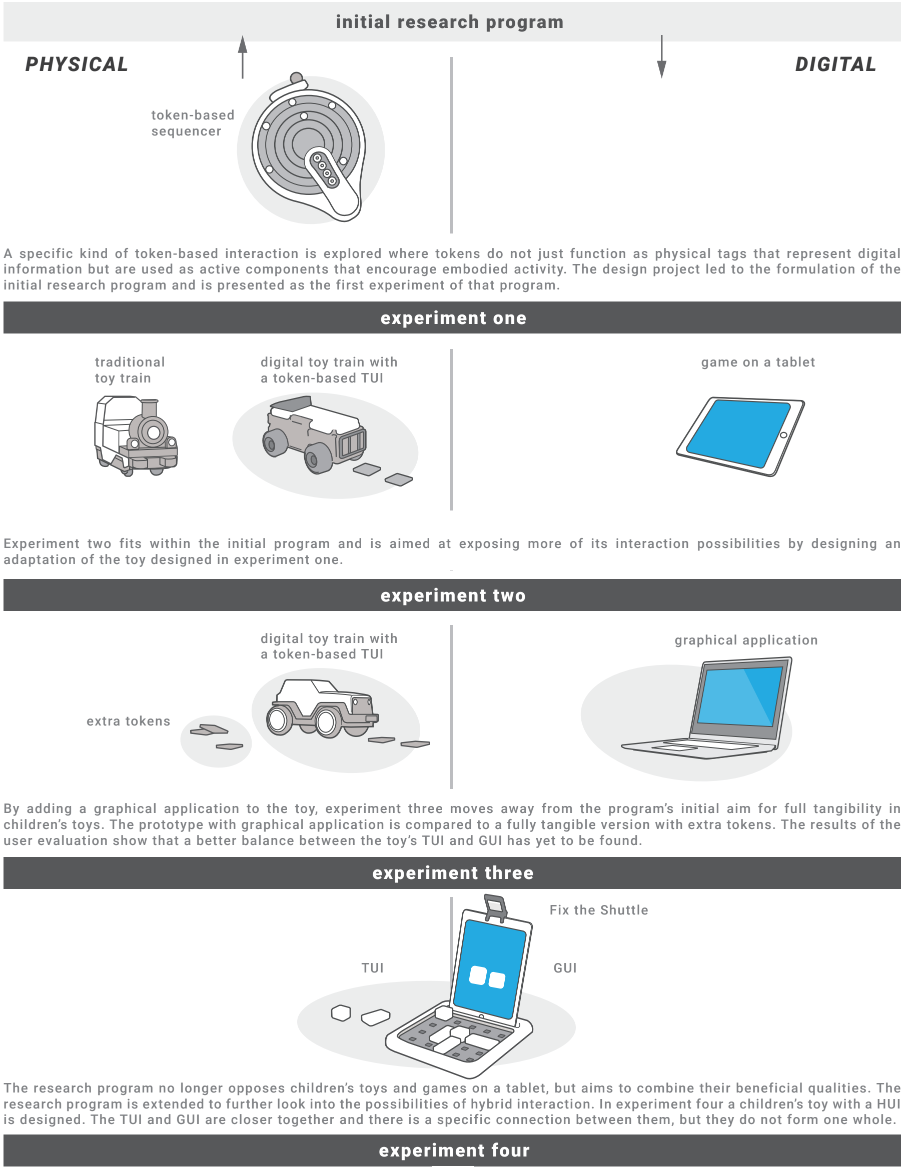


Figure 38 Evolution of the RtD process and research program.

Chapter six:
Hybrid synergy framework

6.1 Introduction

The broad aim of experiment five is to investigate how to blur the border between the physical world and the digital world so that the TUI and the GUI in a HUI can form one whole. However, instead of holding on to the initial research program, a new research program is developed. The previous program was based on existing concepts from tangible and token-based interaction. These concepts were relevant at the start of the trajectory, but do not fully grasp the new research direction. The new research program replaces the terms 'TUI' and GUI' by the terms 'physical half' and 'graphical half' and is founded on the assumption that when both halves are together and combined in the right way, they produce a better and new kind of interaction and experience than when they are separate. However, both halves are distinct and hard to reconcile. This chapter investigates how the concept of coupling can be used to unite both halves. A new framework is developed which explores the synergies between the physical half and the graphical half. This framework is called the hybrid synergy framework and builds further on the aesthetics of coupling framework (Van Campenhout, Frens, Vaes, & Hummels, 2020). A prototype of a children's puzzle is designed in order to explore a first way to achieve synergy between the toy's physical half and graphical half. In this prototype synergy is achieved between the two halves by establishing a causal relationship between both based on physical laws.

6.2 A new research program

Till this point, the thesis largely adopted the concepts of early tangible interaction which is aimed at bringing the digital world made of digital information out in the physical world made of physical objects. In order to find a new direction to move forward, the thesis gradually moved away from the early tangible interaction perspective. Four experiments were required in order to expose a new direction to pursue. The Fix the Shuttle prototype designed in experiment four points to such a new direction. The Fix the Shuttle prototype demonstrates a particular bond between the TUI and the GUI. The TUI and the GUI are not separate entities, but instead the GUI follows the movement of the physical objects in the TUI.

However, this new research direction drifts too far from the initial research program. Because of this, the existing concepts that are used in the initial research program, do not allow to fully grasp the essence of the particular kind of interaction that is aimed for. Hence, In order to fully explore this new research direction a new research program is needed.

The initial research program adopted existing concepts and opposed what are called TUIs and GUIs in the context of children's toys. At first, the TUI is considered the better, more embodied one of the two. However, along the way the research program starts to recognize the beneficial qualities of GUIs and moves away from the research program's initial aim for full tangibility in children's toys in order to find an ideal blend between the two. To do so, the new research program does not hold on to the terms 'TUI' and 'GUI', but instead proposes the concept of two halves: a physical half and a graphical half. The new research program is based on the idea that both halves by themselves are just halves, they need each other in order to become one whole. Both halves consist of distinct types of content.

The physical half consists of physical content. Physical content is the collection of all physical means a designer of digital products can use to make digital information available to humans. Digital information can be embodied in separate physical objects or tokens, but digital information can also be embodied in the physical, hardware properties of digital products through their form, size, texture, material, and movement.

The graphical half consists of graphical content. Graphical content is the collection of all graphical means a designer of digital products can use to make digital information available to humans. Digital information can be made available through various graphical visualizations such as separate graphical objects like icons, menu's, windows, and characters (1), or static and moving images such as photos, and videos (2), or graphical effects such as zoom effect, blur, and transitions (3).

Physical content and graphical content are distinct and have opposite characteristics. Physical content belongs to the physical world and are tangible, static, and persistent, whereas graphical content belongs to the digital world and are intangible, dynamic, and transient (Van Campenhout, 2016, p. 31). For example, the physical building blocks in the Fix the Shuttle prototype belong to the physical world since they are made of physical matter and cannot be detached from the physical world. These physical building blocks are tangible, meaning that they can be touched and felt. The physical building blocks are static and will not move by themselves, unless they are actuated or some external force is applied to them. Furthermore, these blocks are persistent, they do not suddenly disappear or deform.

Unlike the physical building blocks, the character displayed on the tablet's display in the Fix the Shuttle prototype belongs to the digital world because it is stored somewhere in digital form and is composed of the ones and zeros that make up the digital world. It is intangible because unlike physical building blocks, the character does not have a physical shape which can be touched and felt. The character is dynamic in ways that physical content cannot be. The character is transient, it can suddenly disappear or take totally new appearances.

Because physical content and graphical content have opposite characteristics, they are hard to reconcile (Van Campenhout, 2016, p. 33). In order to reconcile them, the research program employs the concept of coupling. Different interpretations of the concept of coupling are discussed in the next section. Finally, the research program proposes its own interpretation.

6.3 Coupling

The concept of coupling on which the various interpretations discussed in this section are founded, is the one described by Dourish (2001). By coupling, he means "the way that we can build up and break down relationships between entities, putting them together or taking them apart for the purpose of incorporating them into our action" (Ibid, p. 138). He gives the example of a hammer. A hammer is a tool which is separate from the user. But when the user uses the hammer, his arm and the hammer form a single unit, or in other words during the action of hammering, the user and the hammer are coupled (Ibid, p. 139). Coupling here refers to a relationship between the user and the equipment in order to effect action. However, Dourish merely gives a description of the concept of coupling, but provides no concrete techniques for designers.

Wensveen, Djajadiningrat, and Overbeeke (2004) have been the first to effectively translate the concept of coupling into a design framework for industrial design. Their interaction frogger framework is developed to make people's interaction with interactive products more intuitive. The framework suggests that when user action and product reaction are united in time, location, direction, modality, dynamics, and expression, they appear to be naturally coupled (Ibid). They state that in most mechanical products user action and product reaction are naturally coupled (Ibid). As such, Table 7 explains these six unification aspects with the example of cutting paper with a pair of scissors as described by Wensveen,

Table 7 The unification aspects of the interaction frogger framework are explained with the example of cutting paper with a pair of scissors. In this example user action and product reaction are naturally coupled for all of these interactive aspects.

	a pair of scissors
time	There is no delay between the movement of the user's fingers, the movement of the scissor's blades, and the incision being made in the paper.
location	The scissors become an extension of the user's hands when cutting the paper. The paper is cut where the scissor's blades touch the paper.
direction	The direction of the incision is the same as the direction of the scissor's blades that follow the direction of the user's hands.
dynamics	The speed of the cutting action determines the speed of the incision being made. A smooth and continuous motion of cutting, results in a smooth and flowing incision.
modality	When the scissor's blades touch and cut the paper this can be seen, heard and felt.
expression	The user can express himself/herself in the cutting of the paper. When the user is in a hurry, his/her actions are likely to lead to imprecise incisions in the paper.

Djajadiningrat, and Overbeeke (2004). Mechanical products, generally offer a more natural interaction than today's digital products this thesis eludes to. For example, compared to a pair of scissors, the traditional desktop PC with mouse and keyboard offers unification on only one of the six aspects, namely time. There is no delay between pressing the button of the computer mouse and the reaction displayed on the computer's display. A smartphone with multi-touch display offers unification on three of the six aspects, namely time, location, and direction. Instead of using a separate computer mouse, one's fingers' actions are spatially linked to the 'on-screen' reactions.

Later Van Campenhout, Frens, Vaes, and Hummels (2020) used the same elements from Wensveen's interaction frogger framework to set up a specific aesthetics which emerges when physical events and graphical events are coupled. They consider coupling as a connection between events in a user-product interaction routine, rather than a connection between user action and product reaction (Ibid). Their framework called the aesthetics of coupling places emphasis on the beauty that stems from the impossible relationship between persistent and temporal events. They describe persistent events as all events that feel permanent and static and that people consider as belonging to the physical world. Temporal events instead feel temporal and fluid and are experienced as belonging to the digital world.

Within this research program the concept of coupling is used in yet another way. As discussed, the studies that have initially inspired this thesis are all related to the tangible interaction perspective. These studies mainly focus on representing digital information with physical form. They are concerned with the expressive qualities of physical content: its appearance and its movement. This thesis adds a different dimension to these existing perspectives by emphasizing that physical content is not the only medium that can be expressive. Graphical content also provides highly expressive means for representing digital information, and can be used to complement physical content. The research program embraces both physical and graphical representations of digital information and investigates the synergies between them. A synergy is a mutually advantageous conjunction or compatibility of distinct elements. Synergism refers to the phenomenon exhibited by the combination of distinct elements in which the effect produced by the mixture is not a simple summation of the effects produced by the individual elements. Or, in other words, combining elements together as one leads to a better effect than one would get by simply adding the effects of each separately.

This idea led to the development of a new framework which is called the hybrid synergy framework. The hybrid synergy framework roughly follows the interpretation of coupling of Van Campenhout, Frens, Vaes, and Hummels (2020). Unlike the aesthetics of coupling framework, the hybrid synergy framework does not focus on all digital phenomena or events, but is specifically concerned with coupling physical content and graphical content in order to establish an advantageous combination between them.

As discussed, physical content and graphical content are distinct and hard to reconcile. However, instead of treating them as opposite and separate, they can become complementary and mutually reinforcing, when they are combined in the right way.

Three types of synergies between physical content and graphical content are presented in this thesis. A first hybrid synergy theme is explored in experiment five. The two other hybrid synergy themes are explored in experiment six to nine and are discussed in chapter seven.

Table 8 shows how the hybrid synergy framework proposed in this thesis builds further on the other discussed frameworks that are based on the concept of coupling. The hybrid synergy framework specifically sets out to use the concept of coupling to create an advantageous combination between physical content and graphical content and proposes three hybrid synergy themes or ways to create such an advantageous combination between physical content and graphical content. This will be further discussed in the next sections and chapters.

Table 8 This table gives an overview of the different interpretations of coupling and shows how the hybrid synergy framework extends the concepts of coupling further.

	interaction frogger	aesthetics of coupling	hybrid synergy framework
	Wensveen, Djajadiningrat, & Overbeeke (2004)	Van Campenhout, Frens, Vaes, & Hummels (2020)	-
what?	user action and product reaction	persistent events and temporal events	physical content and graphical content
how?	Six unification aspects: time, location, direction, modality, dynamics and expression.	Four design projects illustrate how persistent events and temporal events can be balanced in a pragmatic way.	Three hybrid synergy themes are proposed that offer concrete ways to establish synergy between physical content and graphical content.
why?	Establish a more intuitive and natural interaction with digital products.	Plays with the elements of the interaction frogger framework in order to set up a specific aesthetics which emerges from coupling persistent and temporal events.	Establish an advantageous combination between physical content and graphical content which is more than the sum or the effect produced by them separately.

6.4 Experiment five: Penguin Explorer

Presentation

The Penguin Explorer prototype is a digitally enhanced children's puzzle. The prototype consists of a gameboard with integrated square display and 3D puzzle tiles that are separate display modules (see Figure 39). There are different types of puzzle tiles (slope, straight track, curved track, igloo, fish hole, crossing with block) that can be connected to each other. The puzzle tiles become active and are able to display graphical content once they are placed on the gameboard.

Similar to the Fix the Shuttle prototype designed in experiment four, the player has to solve a puzzle to guide a character, a penguin in this case, to the end of a maze. To solve a puzzle, the player has to correctly connect the puzzle tiles to form a track of ice blocks in the water so that the penguin can reach the igloo. The penguin thus needs to find a way over the water to the igloo. The gameboard is virtually filled with water. This is displayed by a number of fish that are swimming across the square display.

The game offers multiple challenges by having the maze in different configurations. Unlike the Fix the Shuttle prototype, the Penguin Explorer prototype does not have a miniature robot that moves through a physical maze. Nor does the animated character move through a maze displayed on the tablet's display. Instead, this concept combines 3D physical puzzle tiles with a graphically-displayed penguin character. The physical content and graphical content are not presented separately, but the penguin character is displayed directly on the physical puzzle tiles.

The Penguin Explorer prototype showcases a unique experience achieved by blending physical content and graphical content. The prototype combines the advantages of playing games on a tablet without losing the attractive features of traditional puzzles.

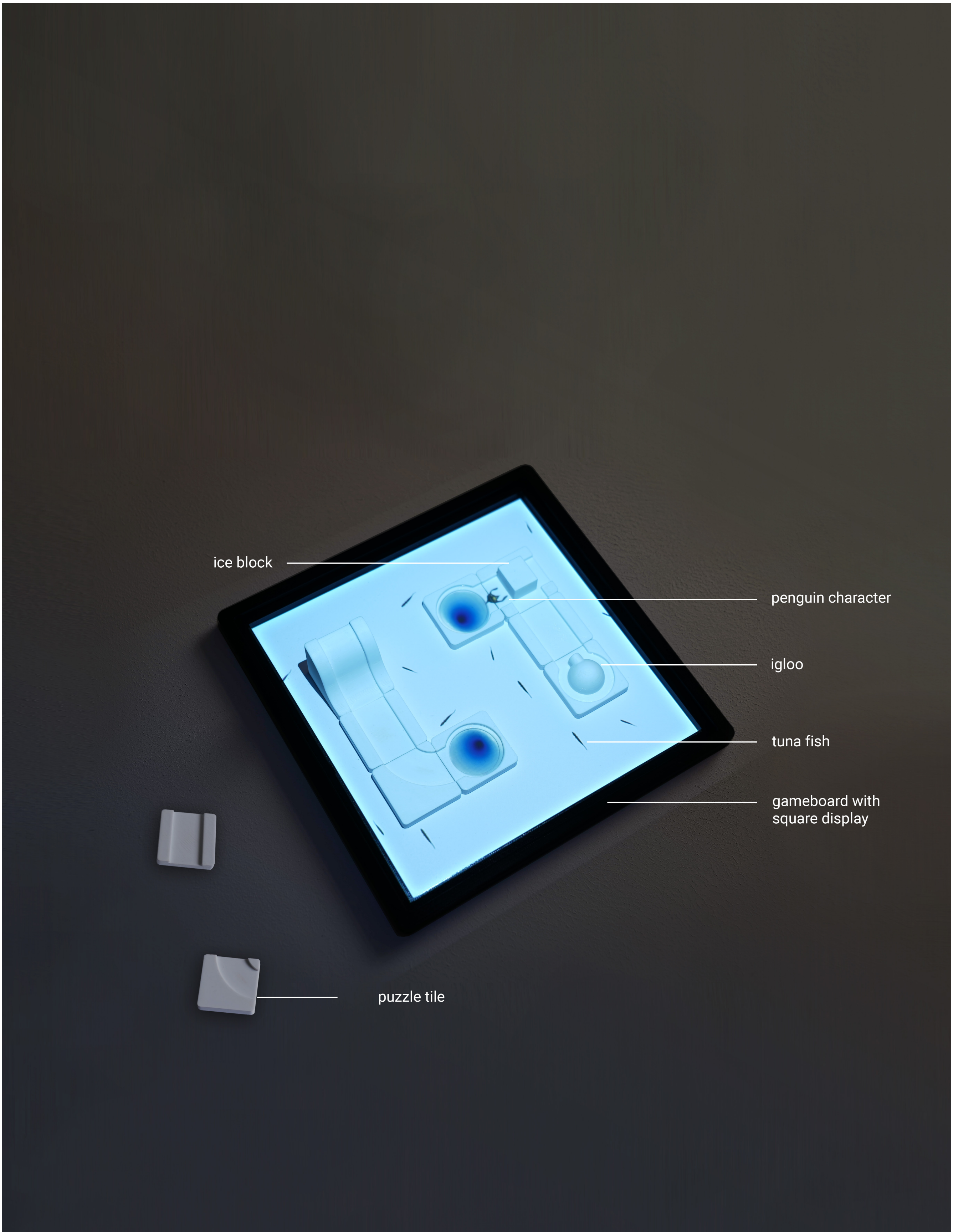


Figure 39 Presentation of the Penguin Explorer prototype and its components.

Prototype development

The prototype is an example of a modular display consisting of separate puzzle tiles that are connected to each other to form one composite display. However, the display technology to develop a ready-to-use prototype is not easily available. Instead two projectors are used to project the graphical content onto the 3D printed puzzle tiles and the gameboard. It requires considerable effort and time to make a fully functional, interactive setup with image recognition, and to allow a shadow-free interaction, and these efforts do not directly contribute to new research insights. Instead, a prototype capable of performing an example of one interaction routine, is developed. The main purpose of the prototype is to be able to make a video demonstrator that demonstrates the synergy between physical content and graphical content.

The 3D shaped puzzle tiles (slope, straight track (2x), curved track, igloo, fish hole (2x), crossing with block) are modelled in Solidworks. These puzzle tiles are printed with Prusa MK3 printers in ICE Filaments PLA 'Wondrous White' (Ice Filaments, n.d.) (see Figure 40). The 3D printed parts are sanded with sandpaper in order to make the material less reflective and to make it suitable for projecting graphical content onto it. The border of the gameboard is printed with Prusa MK3 printers in ICE Filaments PLA 'Brave Black' (Ibid) (see Figure 40). A sheet of white paper is glued under the black, 3D printed border to form a base to project graphical content onto.

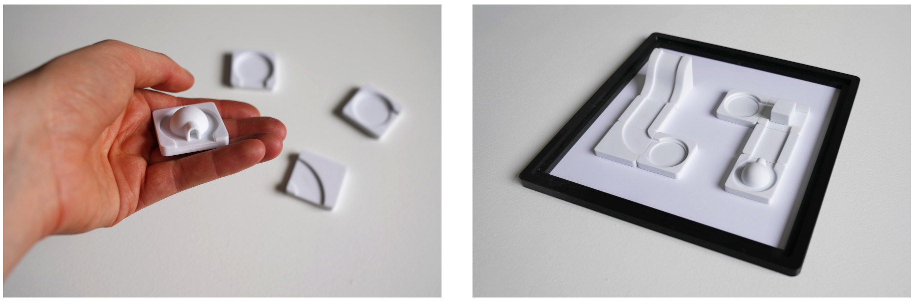


Figure 40 3D printed parts for the Penguin Explorer prototype. Left: 3D printed puzzle tiles. The picture shows a hand holding the 'igloo' puzzle tile. Right: the gameboard with 3D printed border, paper base and 3D printed puzzle tiles.

A detailed 3D character of the penguin (see Figure 41 top-right) is modelled and rigged in Cinema 4D (Maxon, n.d.). STL files of the puzzle tiles are imported in Cinema 4D to create a copy of the physical path (see Figure 41 left). This helps to animate the behaviour of the penguin to match with the puzzle tiles onto which the animated character is projected. Next to the penguin character, a model of a tuna fish (see Figure 41 bottom-right) was modelled, rigged, and animated in Cinema 4D. In the prototype the ground plane is set as water filled with tuna fish. This is to clearly distinguish the puzzle tiles and the gameboard from each other.

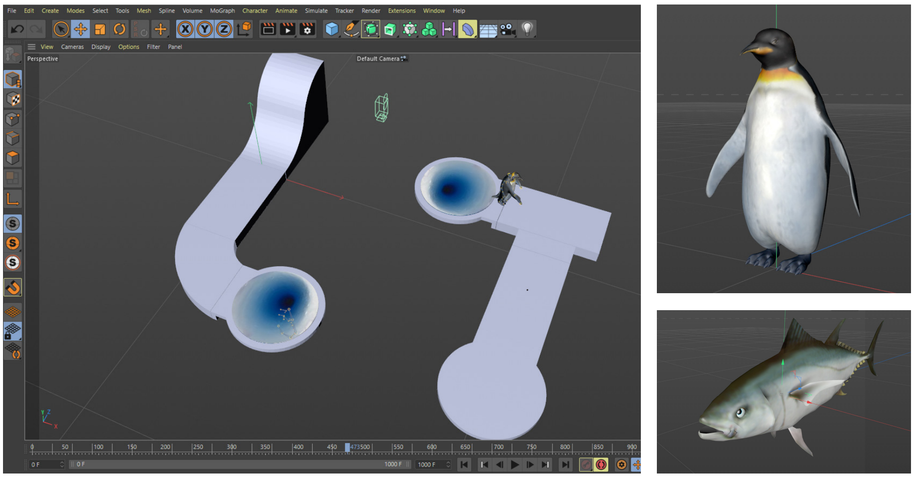


Figure 41 Screen captures of the Cinema 4D viewports. Left: animating the character in a virtual representation of its physical environment. Right: detail of the penguin (top) and detail of the tuna fish (bottom).

A projector setup (see Figure 42) is constructed for making a video demonstrator. This setup includes rear and front projection. The 3D printed prototype (see Figure 40 right) is placed over a cut-out in the tabletop centre. One projector (LG PH550G) is located underneath the tabletop in the stand made from MDF, to project the grid and challenges. Rear projection is used to guarantee shadow-free projection while swiping through the challenges. Examples of these challenges are shown in Figure 43 (left). Another projector (LG PH550G) is located over the prototype to project the animated character onto the 3D printed puzzle tiles. Front projection is needed here in order to project graphical content on the puzzle tiles from above. The projectors are connected to a laptop for displaying the graphical content. The prototype does not offer automated projection mapping but instead manual calibration is necessary to support the mapping of the graphical content onto the physical prototype. Furthermore, an opening in the stand allows the block to be moved manually with the help of a magnet from underneath during filming. For filming a camera mount was positioned in front of the prototype. A Samsung galaxy S10+ model was used to film the interaction.

Figure 42 Picture of the projector setup consisting of a MDF stand and white painted tabletop that is constructed to hold the prototype and to position the projectors for filming the interaction routine.

Description of the interaction

To solve a puzzle the child first has to select one of the challenges. This is done by swiping left or right on the square display (see Figure 43 left). The selected challenge displays the configuration of the puzzle tiles. In order to solve the puzzle, the puzzle tiles need to be placed correctly on the marked locations, so that they form an uninterrupted path to the igloo. An example of a solved puzzle challenge is shown in Figure 43 (right). After placing the tiles correctly on the gameboard, the animation starts playing and shows how the penguin finds its way to the igloo. A video of the penguin moving to the igloo can be viewed by scanning the QR code.

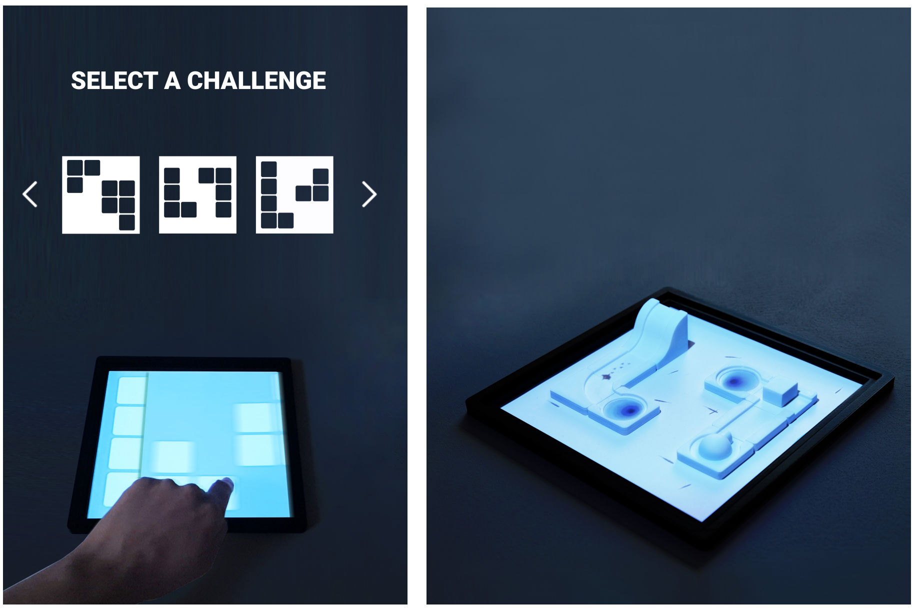


Figure 43 Interaction scenario of the Penguin Explorer prototype. Left: selecting one of the challenges by swiping left or right. Right: watch the penguin as it finds its way to the igloo.

Theme: causality

The first hybrid synergy theme focuses on establishing a causal relationship between physical content and graphical content based on physical laws. This relationship between physical content and graphical content is similar to that in Sir Isaac Newton's action-reaction pairs. Newton states that interaction occurs when two bodies reciprocally act on each other. For every action in nature there is an equal and opposite reaction. Or in other words, if object A exerts a force on object B, then object B also exerts an equal and opposite force on object A. Applying this Newtonian logic to the halves of a digital product, implies that both halves always act in pairs. For every action in the physical half there is an equal, opposite, and simultaneous reaction in the graphical half. In turn, for every action in the graphical half there is an equal, opposite, and simultaneous reaction in the physical half.

The Penguin Explorer prototype demonstrates such a causal relationship between physical content and graphical content. Although, the animated penguin belongs to the graphical half, it does act on and react to the physical half. When the penguin moves over a flat surface, the penguin starts walking. When the penguin reaches the top of the slope, it starts sliding on its belly. The penguin behaves differently depending on what road it is travelling on. Thus, the physical half determines the behaviour of the penguin. In turn, the penguin can seemingly exert force on the physical half. Halfway its journey the road is blocked by an ice block, so the penguin starts pushing the ice block (see Figure 44 left). As a result the ice block slides aside and the penguin can continue its journey (see Figure 44 right).

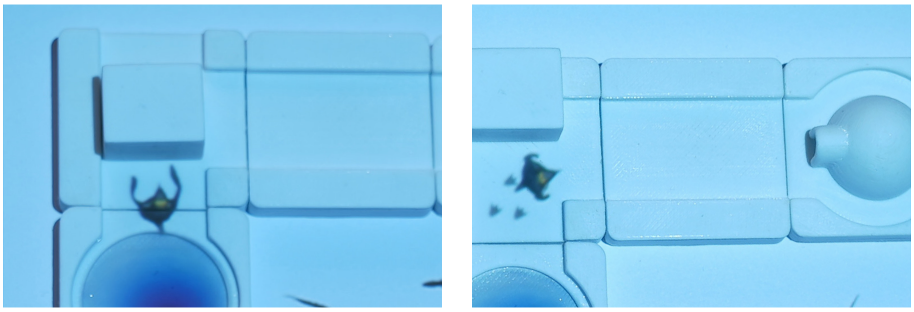


Figure 44 Picture of the penguin pushing against an ice block which is obstructing the road.

The animated penguin character possesses physical properties that go beyond what has been suggested by Djajadiningrat, Wensveen, Frens, and Overbeeke (2004). They state that "a transfer of properties from the physical world to GUIs could lead to folders expressing their contained numbers of items through bulging, their creation date through an aging process such as rust, wear, or yellowing, and amount of disk space occupied through their perceived weight". This is an interesting idea but it goes not beyond a metaphorical level. For example, they suggest the use of a dynamic icon of a folder which appears to bulge or swell when it contains too many items. However, this folder does not really bulge. The Penguin Explorer prototype takes their idea to another level. Namely, the animated penguin character seems to possess real physical properties and is capable of acting on the real world and changing it. This is unusual as graphical content inherently lacks physical properties of its own. For example, a sword used in a game cannot cut; the car you drive in a game cannot be used in the real world to transport you from one place to another (Belk, 2014). This has many advantages. Graphical content is freed from the physical limitations of the physical world in order to take advantage of the unlimited possibilities of the digital world (Van Campenhout et al., 2018). A smartphone does not become heavier when it holds more files, so that people can carry their whole music collection with them in their pocket. Moreover, people can swipe through their files without having to sort out a large pile of printed documents, applying much force, or experiencing any friction. However, this also causes graphical content to be perceived as somehow inherently digital and separate from the physical environment. By subjecting the physical half and the graphical half of the toy to the same laws, both halves become blurred and are experienced as one.

6.5 Discussion: blurring the border

In experiment four a prototype of a programming toy with a HUI that consists of a TUI and a GUI was designed. Experiment four was aimed at finding the right balance between the toy's TUI and GUI. In the Fix the Shuttle prototype, the TUI and the GUI are brought closer together, but do not form one united whole. This is clearly reflected in the border that exists between the TUI and the GUI of the Fix the Shuttle prototype designed in experiment four. The TUI remains on the left side of the border and belongs to the physical world. The GUI is located on the right side of the border and belongs to the digital world. However, the prototype demonstrates a specific connection between the toy's TUI and GUI.

After experiment four a new research program is developed. The new research program does not hold on to the terms 'TUI' and GUI' but proposes the concept of two halves: a physical half consisting of physical content and a graphical half consisting of graphical content. The main motivation of the program is that when both halves are together and combined in the right way, they produce a synergistic effect or a combined effect which is better than one would get by simply adding the effects of each separately. To establish such a synergistic effect the research program investigates different themes.

A first theme, causality, is explored in experiment five. The Penguin Explorer prototype designed in experiment five showcases a specific type of coupling or synergy between physical content and graphical content based on physical laws. Graphical content is made more physical by giving them physical properties and having them obey to the laws of the physical world. Because graphical content almost becomes physical, both graphical content and physical content become more indistinguishable from each other. Or in other words, by blurring the border between the physical half and the graphical half, they appear to be one whole.

With the development of a new research program, the RtD process enters a new phase. Experiment five is the first experiment carried out within the new research program (see Figure 45).

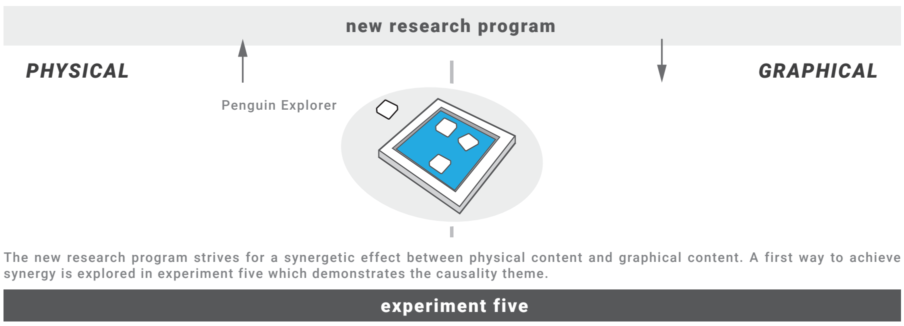


Figure 45 Evolution of the RtD process and research program.

Experiment five pursues the values of embodied interaction which strives to make digital information move out of the digital world of abstract cognitive processes, into the real world in order to enable people to more naturally and intuitively interact with digital information. However, naturalness and intuitiveness are not the only values pursued in experiment five. The prototype developed in experiment five does more than seemingly integrating digital information in the physical environment. Moreover, what it does is more than enriching physical objects with digital information, like it is done in tangible interaction and in the first experiments of this thesis. The prototype achieves a whole new kind of experience that does not exists in the physical, the digital, or in the formerly proposed combinations of both. This compelling and engaging experience emerges by establishing an impossible relationship between two distinct worlds. Blurring the border between the physical world and the digital world, creates a curious experience which does not feel physical, nor digital. Van Campenhout, Frens, Vaes, and Hummels (2020) explain that a specific form of beauty emerges from such an experience which is exactly what defines the aesthetics of coupling.

This sort of experience is not yet present in the Fix the Shuttle prototype designed in experiment four, in the Disney Appmates toy, nor in the Nintendo labo kit and definitely not in the digital toy train with graphical application designed in experiment three. In all these examples, physical objects are designed to complement a game on a tablet (or in the latter one, a graphical application running on a separate computer).

The Disney Appmates toy consists of separate cars and a tablet. The cars are typical small toy cars with rolling tires, designed with attention to details, that are made compatible to the tablet (e.g., their size corresponds to the tablet's display, they include capacitive pads that are trackable by the tablet's multi-touch display). However, the tablet, which is an essential part of the toy, can be used for many different applications other than the Disney race game.

The same can be said of the Nintendo labo kit. The cardboard constructions in the Nintendo labo kit are tailored to a specific mini game and the cardboard controls (e.g., crank handle and push block) are attuned to what is displayed on the tablet's display. However, the weak general tablet which is placed in the cardboard construction, is not designed for that specific mini game, it can be used to play various other mini games and for many other applications. One can say that the cardboard controls are no more than stuck-on cardboard pieces attempting to cover up the physically poor, generic tablet interaction.

This also applies to the Fix the Shuttle prototype designed in experiment four that combines various physical objects with a tablet.

Adding a tablet to the toy obviously opens the door to many graphically-appealing and versatile features which are not supported by fully tangible toys. However, a tablet is a weak general device that has to support various applications. The interaction and display opportunities of the tablet are restricted because of its standardized, generic form. Because of this, the physical content and graphical content of the toy cannot be fully attuned to each other. The designer is limited to design graphical content that is displayed on the tablet's flat, rectangular, and rigid display to then design physical content that goes with it. The Nintendo labo kit does a good a job of designing the physical content around the graphical content displayed on the tablet's display as if they really are one, but essentially it is still a combination of separate, inter-related parts (cardboard pieces and a tablet). This is not the case in the Penguin Explorer prototype designed in experiment five where the physical half and the graphical half of the prototype are specifically and parallelly designed as one whole.

Chapter seven: The Content Specific Display

7.1 Introduction

This chapter looks into different display technology that offer additional display and interaction opportunities compared to the displays that are currently available in the market. This variety of emerging display technologies enable designers to move away from the golden standard that is restricted by its flat, rectangular, and rigid form, in order to create specialized solutions. Diversifying the range of display technology allows the design of specialized displays that reflect a physical commitment to the displayed graphical content. I call such displays Content Specific Displays. The concept sustains the continuous balancing act between physical content and graphical content and allows the investigation of the synergies between them. This chapter presents four additional experiments that provide examples of Content Specific Displays. Finally, this chapter discusses two additional hybrid synergy themes that arose from these experiments.

7.2 Advances in display technology

Chapter six concluded that the generic and fixed form factor of the tablet's display prevents designers to fully attune physical content and graphical content to each other. A new medium needs to be found that enables to design physical content and graphical content as one whole, so that a synergistic effect can be achieved. As such, this section presents different types of future display technology and prototypes that together provide a variety of new solutions. These displays are categorized in the following categories:

Shape-changing displays

Shape-changing displays are graphical output surfaces that support dynamic physical reconfiguration (Hardy et al., 2015). Shape-changing displays include different sorts of actuated displays and various actuated mechanisms covered with display surfaces (Alexander et al., 2018). Shape-changing displays are relevant to this thesis as they have their roots in tangible interaction and are aimed at overcoming the static nature of TUIs by complementing TUIs with the dynamism of the visually perceived affordances of GUIs (Follmer et al., 2013). Shape-changing displays are especially useful here as they can physically reconfigure themselves to better represent or complement the displayed graphical content. They can take the shape of the object or scene which is displayed. Furthermore, shape-changing displays can make the display follow the movement of the dynamic graphical content. This way physical content and graphical content are intertwined to a synchronous experience. This is well demonstrated in the Coca Cola 3D robotic billboard (see Figure 46) developed by Radius Displays (Radius Displays, 2017) which is one of the few and most popular commercial applications of shape-changing displays. The display consists of multiple actuated LED panels which can be moved independently from each other. Radius Displays presents it as a one-of-a-kind display which showcases the synergy between the dynamic graphical content and the moving display panels.

Figure 46 Coca Cola shape-changing display billboard. The actuated LED panels adapt their position to match the displayed graphical content. Pictures courtesy of Radius Displays.

Deformable displays

Deformable displays are another interesting area to discuss. Deformable displays are aimed to replace rigid displays and to exploit the potential of non-rigid interactions (Boem & Troiano, 2019). Deformable displays are said to be the next generation of visual output devices that extend beyond the flat, rectangular, and rigid surfaces of current displays to those that the user can deform or those that facilitate a range of self-deformations to better represent graphical content or to support new modes of interaction (Alexander et al., 2013).

Many studies looked into the potential of displays that can support paper- or cloth-like deformations that can be bent, twisted, pulled, rolled-up, folded, and torn apart just like a piece of paper or fabric.

An interesting example of such a deformable display is the Reflex prototype developed by Strohmeier et al. (2016) which is shown in Figure 47. This prototype is especially relevant to this thesis as it illustrates two example cases in which the physical bend gestures of the user and the displayed graphical content are closely coupled. The user interacts with the graphical content through bend gestures. One case resembles a book by implementing a 'page-flipping' effect. By bending the display, pages flip through the fingers from right to left, just like they would in a book. The more the user bends the display, the faster the displayed pages will flip. Users can feel the sensation of the page moving through their fingertips via vibrations. Another case demonstrates a user playing the Angry Birds game on the Reflex prototype. To stretch a sling shot, the user needs to bend the display. As the rubber band expands, the user experiences vibrations that simulate those of a real stretching rubber band. When released, the band snaps, sending a jolt through the phone and sending the bird flying across the display. The more the user bends the display, the further the launched projectile reaches.

Figure 47 The pictures show two uses cases of the Reflex prototype. Left: user bending the prototype to move through the displayed document as if he/she is flipping through the pages of a book. Right: user bending the prototype to stretch a sling shot in the Angry Birds game. Pictures courtesy of Queen's University's Human Media Lab.

Other types of deformable displays are elastic displays that consist of an elastic membrane onto which graphical content is projected such as the Obake prototype developed by Dand and Hemsley (2013) which is shown in Figure 48.

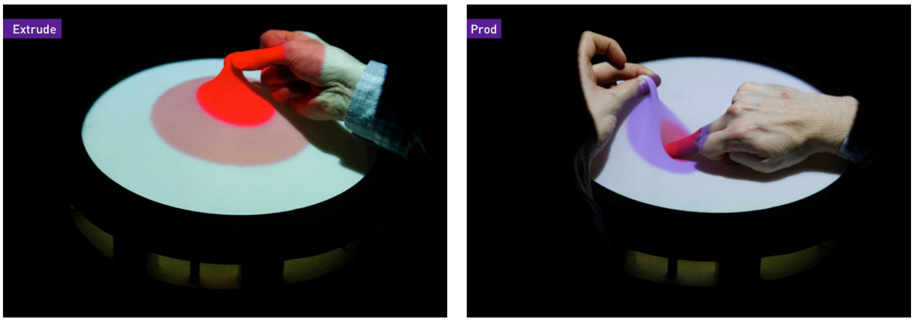


Figure 48 The Obake 2.5 elastic display. Two examples of the interaction language supported by their prototype. Picture courtesy of Dand and Hemsley, 2013.

Or malleable displays that consist of non-translucent sand (as seen in Harmon, 2016 see Figure 49 left), clay, or translucent substrates made of glass beads particles or gels (as seen in Follmer et al., 2012 see Figure 49 centre). Malleable displays allow user actions such as squeezing, kneading, and digging and are especially useful for displaying volumetric or layered graphical content such as landscape terrains, or to display non-planar sections of a 3D image (e.g., the Phoxel-Space prototype is used to show a non-planar section of a human brain (as seen in Ratti et al., 2004 see Figure 49 right).

Figure 49 Left: the Tangible Landscape prototype allows to sculp a terrain in sand. Landscape elements like water and contours are graphically-augmented onto the prototype (Harmon, 2016). Centre: the Tunable Clay prototype is a square malleable display designed to mimic the malleability of clay that can be used to deform or sculpt the displayed graphical content (Follmer et al., 2012). Right: the Phoxel-Space prototype is used for medical imaging and can display non-planar images of a human brain scan (Ratti et al., 2004).

Smart mirror and transparent displays

The category of reflective and transparent displays contain all displays that augment graphical content onto the real-world environment, by either using smart mirror technology (Lee, Park, & Billinghurst, 2019) or see through display panels (Hilliges et al., 2012). This allows the user to literally get into the virtual display and to directly interact with a virtual world, without the need for any specialized head-worn hardware or using projection-based visualization.

There are many examples of science-fiction-like computer devices with transparent displays, but they fail to be anything other than a gimmicky feature. More useful examples of transparent displays are the displays used in vending devices and the ones used in interactive museum booths. The latter enables to exhibit artefacts safely behind glass as well as allowing the visitor to interact with the exhibit while relevant information is displayed next to the artefact. In this particular example below (Figure 50) the user can look through a book by flicking through pages and zooming in, giving the real experience without damaging the historical artefacts.

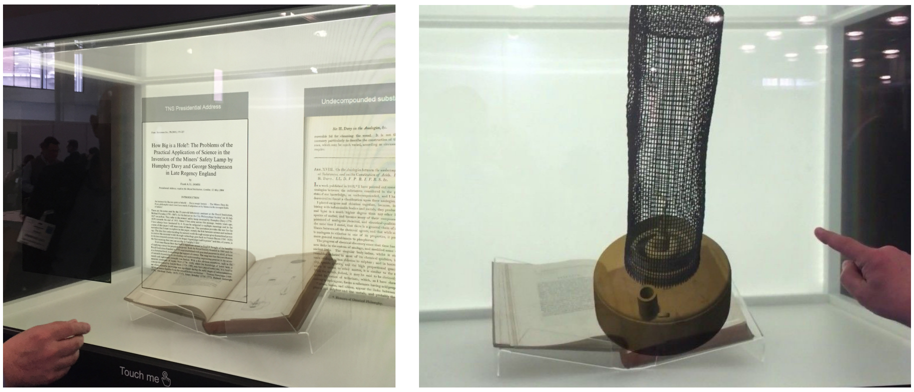


Figure 50 Transparent display used in a museum booth. In this particular example the user can look through a book by flicking through pages displayed on the transparent display and zooming in, without damaging the artefact (left). Next to flipping through the book's pages the visitor can interact with the virtual objects that are presented on the display (right) (CDS, n.d.).

Modular displays

Modular displays are all displays that include a plurality of tiles or cells which are abutted together to form a composite display. Modular displays offer the flexibility of modularity with the ability to customize the display to a variety of sizes and designs according to the spatial and user needs. Examples of modular displays found in literature are the PickCells prototype developed by Goguey et al. (2019) and the CubiMorph prototype developed by Roudaut et al. (2016).

An example of a toy application demonstrating the utilization of modular displays are the Sifteo Cubes (Merrill, Sun, & Kalanithi, 2012) which are a commercialization of the Siftables (Merrill, Kalanithi, & Maes, 2007) developed at the Fluid Interfaces group at MIT. Sifteo Cubes are compact devices equipped with an accelerometer, colour Liquid Crystal Display (LCD) multi-touch display top, and wireless communication; that afford two-handed manipulation of graphical content. Sifteo Cubes support various mini games based on couplings between the graphical content displayed atop and the physical manipulation and arrangement of the modules. Examples of such mini games are the Ice Palace™ mini game of the Sandwich Kingdom franchise (see Figure 51 right) and the Chroma Shuffle™ mini game (see Figure 51 left). These mini games are presented in (Sifteo, 2011), a video can be viewed by scanning the QR code.

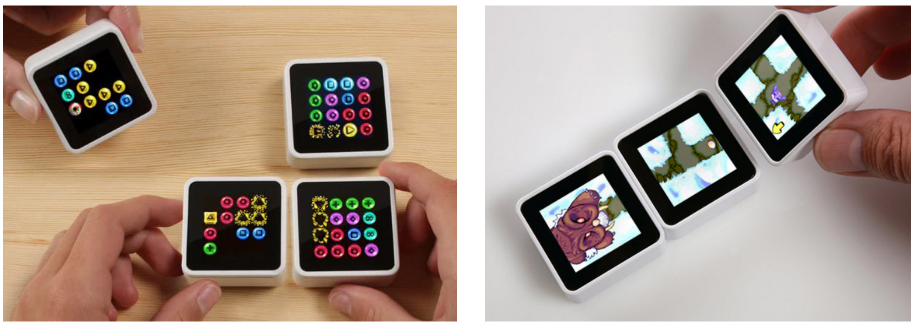


Figure 51 Two examples of mini games available on Sifteo Cubes. Left: in the Chroma Shuffle™ mini game players need to connect the cubes together so that same coloured dots on adjacent cubes explode and clear. Right: in the Ice Palace™ mini game players need to arrange the different modules or cubes to reveal a path through the frozen north for a character named Cobb. Pictures courtesy of Sifteo Cubes.

Another example of modular display technology is demonstrated by Samsung. Samsung has started to commercialize modular microLED display panels that are designed to be mounted together as a uniform canvas (Samsung, n.d.). To promote their modular microLED panel technology Samsung has developed installations consisting of multiple moving display panels (Fox, 2019; Larsen, 2016). These installations demonstrate a good example of a synergy between the displayed graphical content and the spatial configuration of the display panels. Each individual panel displays an animation of a dancing figure that is synchronized to the movement of the display panels (see Figure 52). The dancers displayed on the individual panels can only dance together once the display panels are linked to each other. The effect of linking the display panels is even more powerful by the accompanied animation of the dancers being pulled to each other, to then be pulled back to their own display panel once the display panels are separated.

Figure 52 Samsung's modular LED panels demonstrate a close synergy between the movement and spatial configuration of individual display panels and the animation displayed on the panels. Left: the panels are separated from each other and display a dancing figure. Right: the panels are linked to each other so that the dancers displayed on the individual panels can dance together. Pictures courtesy of Samsung.

Non-rectangular displays

The displays of today are defined by their rectangular shape. Round shaped displays are more frequently used in wearables such as smartwatches or in products like Google Nest. Emerging technologies allow for the creation of non-rectangular displays with unlimited constraints in shape (Serrano, Roudaut, & Irani, 2016), both 2D and 3D, e.g., spherical display (Benko, Wilson, & Balakrishnan, 2008).

Novel display form factors give designers more freedom to spatially manage graphical content and to arrange it better than one could do on a rectangular display. The behaviour of the graphical content can be affected by the physical properties of the display such as displays having holes, bumps, or textures. Furthermore, the display form can be designed to better fit into the product, such as in-vehicle displays that neatly fit into the car's dashboard (Simon, Roudaut, Irani, & Serrano, 2019).

7.3 The generic qualities of displays

As discussed in the introductory chapter much of HCI today is confined to flat, rectangular, and rigid displays and traditional GUI interaction. The previous section provides an overview of alternative display technology found in literature and in the market that offer additional display and interaction possibilities and that may offer new means to reach the synergistic effect that the hybrid synergy framework strives for. Many of these displays have a very distinctive, unique character and are only suitable for very specific applications. For example, no one is going to use the TiltStacks prototype (Tiab et al., 2018) for reading the newspaper or browsing the internet (see Figure 53).

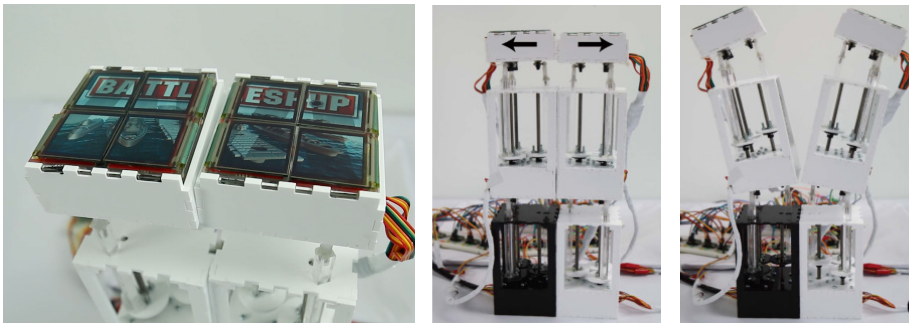


Figure 53 The TiltStacks prototype (Tiab et al., 2018) has unique physical features which are not compatible with a wide range of content. The TiltStacks prototype is here used for playing Battleship (left). The Battleship gameplay requires that the two players have a private part of the display so as not to reveal their fleet layout. TiltStacks starts as a single continuous display (centre), then splits into two halves where each half moves towards a player to provide privacy for the players (right).

The emergence of diverse and unusual displays enables designers to look for solutions other than the standardized GUI design and to instead choose for specialized, one-off designs. However, the idea of designing highly specialized interfaces is against the general trend of convergence in HCI.

Convergence argues for the coming together of a variety of different information streams in one single device (Dourish, 2001) and enables the combination of multiple functionalities in one device. Convergence has made it possible for people to play games, send text messages, and manage their bank account all with one device. Proponents of convergence (Forman & Saint John, 2000) argue for clear user benefits: with multi-purpose, single-device solutions people will be able to do more things with one system and need to own fewer devices (Howard et al., 2004). Opponents of convergence (Buxton, 2001; Norman, 1999) state that convergence produces clumsy, generic devices that overwhelm the user with options (Howard et al., 2004). Buxton (2001) has a term for these devices, he aptly calls them weak general systems.

"Weak general systems can do a lot of things, hence their generality, but for many of these there are other tools that can do better, hence their relative lack of strength."

Divergence instead leads to devices that are tailored to one specific function and thus can be appropriated entirely to that function (Ibid). Such systems are also called strong specific systems.

"A strong specific system can only do a few things, hence its specificity. However, what it does, it does better than the general purpose system. Hence its strength."

Other researchers such as Djajadiningrat, Wensveen, Frens, and Overbeeke (2004) and Van Campenhout, et al. (2016) state that the argument for divergence is not limited to usability aspects, but that a divergence-oriented approach also makes room for other values such as expressiveness and aesthetic quality.

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[15] *Weak and strong are used here to refer to hedonic qualities pertaining to enjoyment ('joy-of-use'), playfulness, attachment, aesthetics of interaction, and user experience. In a strong specific system these qualities are valued over performance-oriented qualities such as multi-functionality, efficiency, flexibility, versatility. Strong specific systems strive to extend the functional in order to provide hedonic benefits.*

The debate over convergence and divergence approaches in HCI has been an old one and was a response to function specific appliances and products increasingly being absorbed by the desktop PC. This chapter picks up the debate again, but from a different angle. Here, attention is drawn specifically to the generic qualities of displays. Today's displays have a generic form regardless of the content that is displayed. The display of a smartphone is not specifically designed to display one type of content, but supports a variety of different content, such as videos, games, websites, pictures, text messages, etc. In turn, the displayed content is generic and largely display independent. The content displayed on your smartphone is not specifically designed for your smartphone's display, but is compatible with other types of smartphones and other display devices. When the same content is displayed on a different display, the content does not change, but only adjusts to the size of the display.

However, some displays that are designed for specific, professional or public context of use, are dedicated to one specific type of content. Examples of such displays are displays used in airplane cockpits (see Figure 54 left), diagnostic displays used for medical imaging, and display boards showing train departures (see Figure 54 right). Yet, even these displays do not exhibit any unique traits. Compared to regular displays, these displays may have improved technical specifications (e.g., diagnostic displays have increased brightness and superior image contrast as standard desktop displays will be unable to meet the requirements for supporting medical imaging applications, such as X-ray, PACS, MRI), but their form factor remains identical to those of regular displays.

Figure 54 A display used in an airline cockpit displaying flight navigation maps (left) and a display on a train platform (right) support different content, but are identical in form. Pictures taken from Thales, 2019 and Dysten, 2020.

7.4 The Content Specific Display

The previous section addresses the issue that displays are generic and that even displays used in very specific or specialist situations do not offer alternative designs that are superior to the weak general, golden standard that has to support a wide range of different applications and content. It is strange that these specialized displays do not seem to provide any unique traits compared to the standard desktop display sitting on one's desk knowing that there are now a range of different display technologies available that enable the development of single case designs that are more attuned to their specific application and content.

Instead of choosing to converge all form factors to a single, flat, rectangular, and rigid display, this chapter looks at what a future with diverse forms of displays may look like. To do so, this chapter introduces a new concept termed the 'Content Specific Display'. Content Specific Displays are displays that are tailored to a single type of content and thus only support content specifically designed for that type of display. The Content Specific Display can reflect a physical commitment to the displayed graphical content. In that way, the concept sustains the continuous balancing act between physical content and graphical content and allows the further investigation of the synergies between them. It is a condition or a means to reach a synergistic effect between physical content and graphical content. Or in other words, it is difficult to reach synergism between physical and graphical content without the Content Specific Display.

This chapter presents four experiments that provide examples of Content Specific Displays. Each experiment uses one of the display technologies presented at the beginning of the chapter and applies it in a specific product application.

Finally, this chapter discusses the two hybrid synergies that arose from these experiments. All three themes are further discussed in chapter eight.

7.5 Experiment six: Furo

Presentation

The Furo prototype is designed by Anthony Collin, Christophe Demarbaix, and Jasper Verschuren. The prototype is the result of the Interaction Design (IxD) project organized for the first year master students Product Development at the University of Antwerp. The prototype features a curved display. The students designed a concept of a drink dispenser which works as a digital water tap equipped with a display. The prototype demonstrates a direct link between the flowing of the water, the physical shape of the tap and the displayed graphical content. All elements are harmoniously united in one design. The prototype is presented in Figure 55.

Figure 55 Presentation of the Furo prototype and its components. Left: user pulling the slider to fill the reservoir. Top right: the tap is in rest state. Red, liquid substance is displayed on the platform under the tap and shows that the tap is ready to be used. Bottom right: glass bowl being filled with the water from the reservoir.

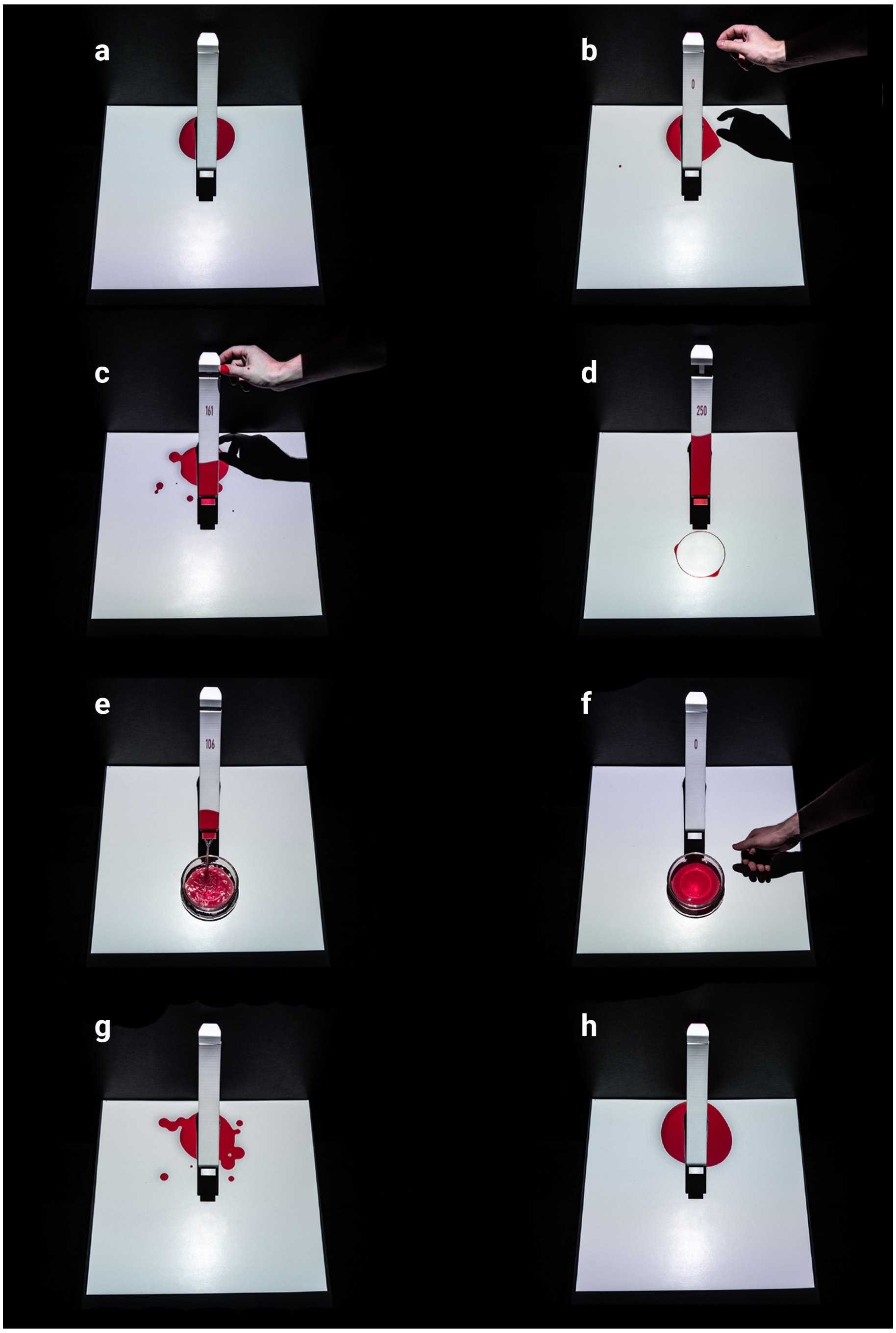

Figure 56 Interaction scenario of the Furo prototype.

Description of the interaction

The prototype is a digital water tap that consists of a physical reservoir which seemingly absorbs a graphically-displayed red, liquid substance to then fill a glass bowl with the water from the reservoir. When the prototype is in rest state, an animation of a red, liquid substance is displayed on the platform under the tap (Figure 56a). This indicates that the tap is ready to be used. By moving the slider at the end of the tap, one can virtually fill the reservoir with water (Figure 56b). The further the slider is moved, the more water the reservoir absorbs. This action is accompanied by an animation that displays the filling of the reservoir (Figure 56c). This gives the user a visual indication of how much water the reservoir contains. After this, the user is asked to place a glass bowl under the tap. A graphical mark on the platform indicates where the bowl is to be placed (Figure 56d). Once the bowl is placed in the right location, it is filled with the amount of water stored in the reservoir (Figure 56e). Finally, the user is asked to remove the glass bowl from the platform (Figure 56f). After removing the glass bowl, the prototype returns to its rest state (Figure 56g,h).

Theme: unification

A first hybrid synergy theme is demonstrated in the Penguin Explorer prototype. The Penguin Explorer prototype demonstrates a causal relationship between physical content and graphical content based on physical laws. This theme is also demonstrated in the Furo prototype. The graphical content is again approached in a very physical way. The graphically-displayed red, liquid substance behaves almost like real water. However, in the Furo prototype the focus is set on a new hybrid synergy theme.

The second hybrid synergy theme aims to unite the physical half and the graphical half so that they can form one whole. This theme is found on the assumption that by uniting physical and graphical content in one balanced, harmonious whole, a more natural interaction with digital products can be achieved. The unification theme is based on the idea that each half expresses only part of the information to the user and thus needs to co-operate with the other half to give the user all the information he/she needs. Or in other words, the physical half and the graphical half are not sufficient on their own but need each other to effectively deliver information to the user about the product's use.

A product can give information to the user through its expressive physical form in order to guide the user’s action towards the intended function. This is seen in the

Furo prototype for example in the slider at the end of the reservoir which can be pulled upward. The curved shape of the tap suggests and sustains this upward movement. The pulling of the slider or the filling of the reservoir can be seen, and felt, and the movement of the sliding mechanism may even be heard.

Unlike physical content, graphical content cannot be felt or heard. Graphical content is more suited to express the temporal dynamics of the interaction process as it plays out over time, since graphical content is animated far more easily than physical content. Because of their dynamic character, graphical content can more easily reflect moods and temperaments such as urgency, frustration, and nervousness. This is seen in the Furo prototype for example in the red, liquid substance displayed under the tap which is trying to attract the user's attention by moving nervously. This way it tells the user that the product is in rest state and ready to be used.

The Furo prototype demonstrates a close cooperation between the physical half and the graphical half. Both halves come together to form one whole and work together. When working together, the physical half and the graphical half are at all times in sync and connected. In order to match, both halves have to be naturally coupled on each of the unification aspects (time, location, direction, dynamics, modality, and expression) described by Wensveen, Djajadiningrat, and Overbeeke (2004).

When the user starts pulling the slider which belongs to the physical half, the red, liquid substance displayed on the platform which belongs to the graphical half, responds and is being absorbed into the reservoir. At the same time, the reservoir fills itself graphically with the red, liquid substance (time).

The more the slider is pulled, the more liquid is extracted from the platform. The graphical content displayed on the reservoir also indicates how much space there is left in the reservoir and thus tells how much further the slider can be pulled. The length of the slider needs to correspond with the amount of red, liquid substance displayed on the reservoir (location).

The movement of the red, liquid substance filling the reservoir follows the upward movement of the slider (direction).

Moving the slider faster corresponds with the displayed, red, liquid substance moving upwards faster (dynamics).

What is seen by the user must correspond with what is felt and heard (modality).

Moving the slider faster, reflects a sense of urgency, which is also reflected in the intense or more nervous movement of the red, liquid substance (expression).

The unification theme assumes that physical content and graphical content should be connected and in sync in order to establish an intuitive interaction which matches the expectations of the user. For example, when there is a delay between the pulling of the slider and the animation of the red, liquid substance filling the reservoir, or worse when the amount of red, liquid substance displayed on the reservoir does not correspond with the length of the slider, the product may be perceived as defect or unreliable.

7.6 Experiment seven: Curtains

Presentation

The Curtains prototype is the result of the MSc thesis of Thomas Verstrepen, a second year master student Product Development at the University of Antwerp. The prototype is a display with cut-outs which is combined with physical tools. These tools, which do not contain interactive elements, enable the user to physically interact with graphical content in both size and colour.

Description of the interaction

The prototype consists of a display, a white, coin-shaped token and two identical physical tools (Figure 57a). First, the user inserts the token in the display. The physical token disappears into the slot. At the same time a graphical representation of the token appears on the display (Figure 57b). The graphical representation of the token moves towards the centre of the display (Figure 57c). The user then picks up the tools and brings them to the display (Figure 57d). The tools are non-interactive, physical objects. Once they are hidden behind the display, their static, physical form transforms into dynamic, graphical tools. Unlike their physical counterpart, these graphical tools are interactive and respond to the actions of the user. It is as if the physical tools come to life as soon as they are behind the display. Next, the user moves the tools closer to the token (Figure 57d). When they are near the token, the tools grasp the token. Now the user can move the tools to scale the size of the token (Figure 57e). Once the token is scaled, the

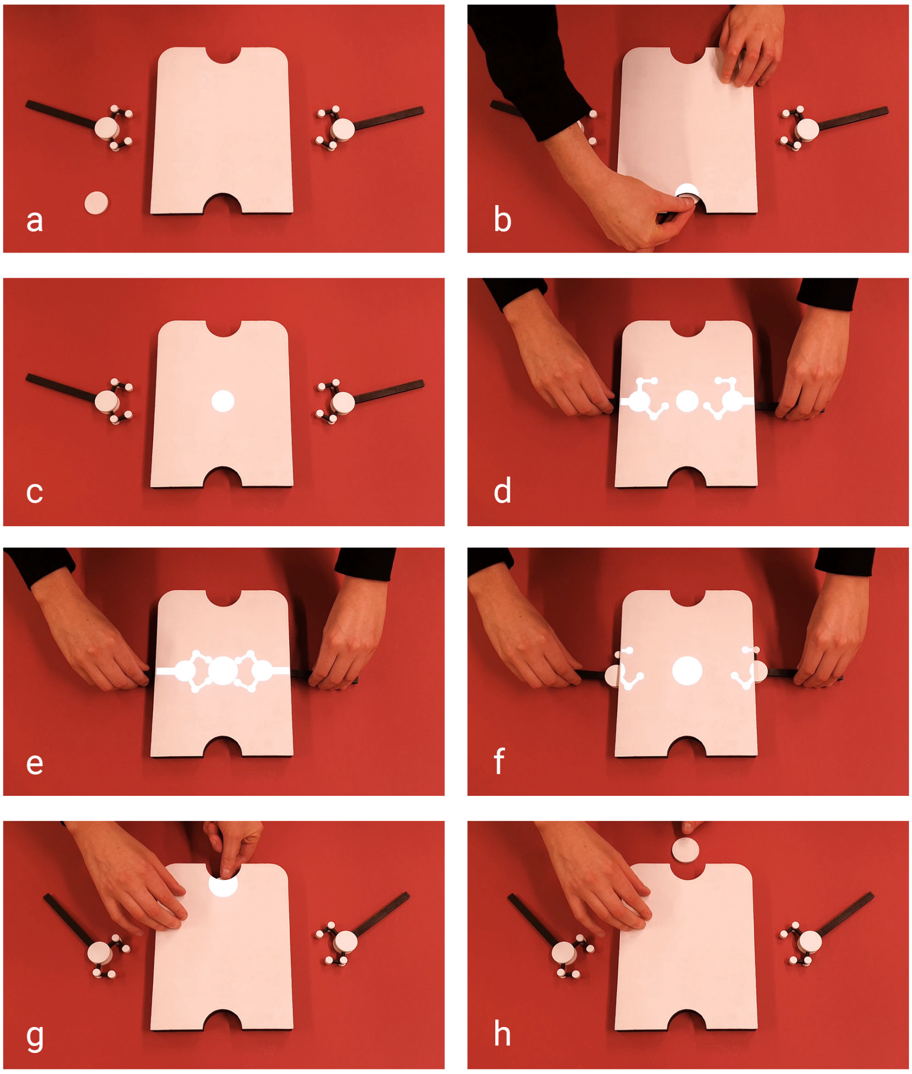

Figure 57 Interaction scenario of the Curtains prototype.

user pulls the tools back (Figure 57f). Their physical form reappears, while their graphical counterpart leaves the display. After this, the graphical representation of the token moves downwards, until the token physically appears at the bottom of the display. Now, the user can pull the token out of the slot (Figure 57g). The token transforms again to its initial physical state, but is scaled (Figure 57h). A video of the interaction scenario can be viewed by scanning the left QR code. A video of a similar interaction scenario with the curtains prototype can be viewed by scanning the right QR code below. This video shows how a different physical tool is used to virtually paint the token.

Theme: transformation

Next to the previous themes (causality and unification) a third theme is demonstrated in this prototype. This third theme is based on the transformation of physical content and graphical content. Instead of choosing between physical content or graphical content, one object can have two states, a physical one and a graphical one. Both states cater different interaction possibilities. During the interaction the objects frequently switch between both states depending on which one is preferred for the particular situation.

The Curtains prototype demonstrates this unique interplay between physical content and graphical content. The display is used with a token and physical tools. These physical objects transform into their graphical counterpart once they are hidden behind the display. Both states allow different actions. In their physical state the objects can be easily grasped with your hands and enable physical interaction. These physical objects are static and only become interactive once they disappear into the display and their graphical counterpart takes over. The display serves as a magical window into the digital world, where the physical tools are interactive and the otherwise fixed token can be easily manipulated and scaled. The prototype goes beyond blurring the border between the physical world and the digital world to remove the border between them. In the prototype, the token is scaled in its graphical state, but remains scaled when it returns to its physical state. Or in other words, the token is scaled in the digital world, but remains scaled in the physical world. The digital world can have real impact on the physical world. This seems impossible, and therefore even more captivating.

The transformation theme is also present in the Furo prototype designed in experiment six. The red, liquid substance displayed on the reservoir turns into water.

7.7 Experiment eight: Myoo

Presentation

The Myoo prototype is the result of the MSc thesis of Eva Van Emelen, a second year master student Product Development at the University of Antwerp (Universiteit Antwerpen, 2019). Myoo is a product service system that supports young people with Irritable Bowel Syndrome by offering a health monitoring system with drug therapy management and a drug delivery service. The prototype consists of a smart mirror display with multidose drug dispenser that contains pre-packed Myoo Pods which contain the pills (see Figure 58). The prototype saves information about the patient's health and medical history in the online application. The total package enables young people to self-manage their treatment. The treatment involves keeping track of symptoms such as bowel movement, and fatigue to estimate the patient's physical and mental health and determine the right drug dose. Compared to other drug dispenser solutions more attention is paid to the illness experience and psychological impact of the illness on the patient. Hence, Myoo uses a smart mirror to confront patients with themselves, so that they can manage their illness more confidently and consciously.

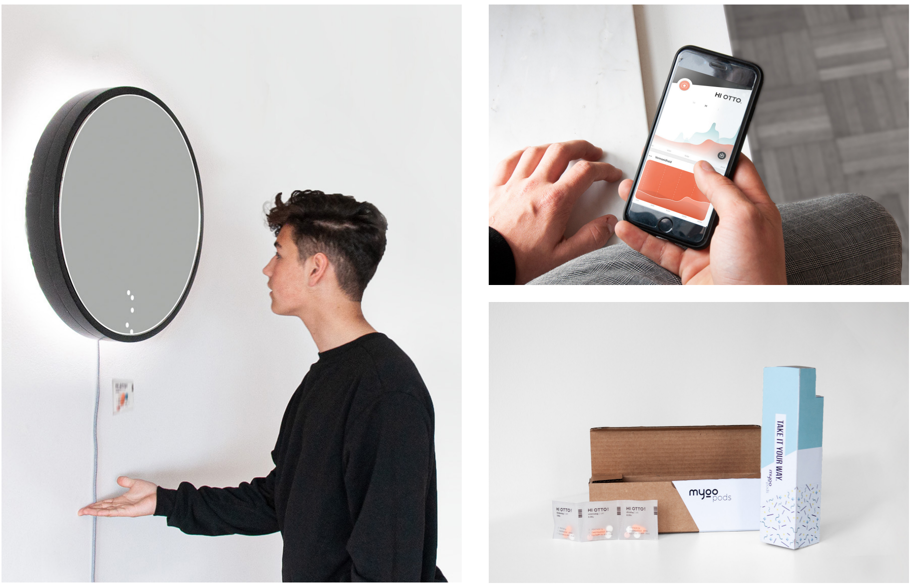

Figure 58 Left: presentation of the Myoo prototype. Top right: the application displayed on a smartphone. Bottom right: the Myoo pods.

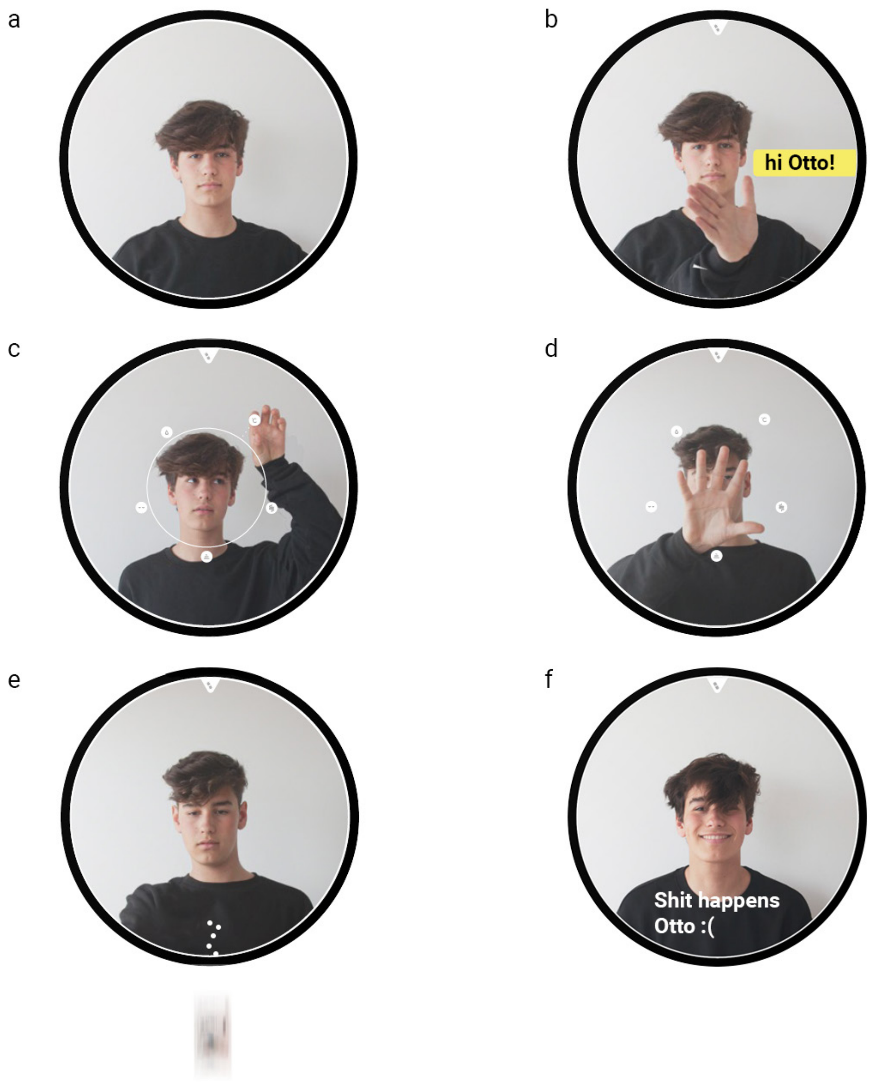

Figure 59 Interaction scenario of the Myoo prototype.

Description of the interaction

A functional prototype is developed which features a round smart mirror with multi-touch display. The prototype is activated by facial recognition technology. This means that the product is activated once you stand in front of it (Figure 59a). When activated, Myoo starts displaying messages. The user can respond to these messages via gesture control. For example, swipe left to save a message, swipe right to delete a message (Figure 59b). After displaying all new messages, the patient is prompted to complete the daily medical report (Figure 59c). There are five different symptoms that are evaluated in this medical report: stool, bowel movement, fatigue, fever, and joint pain. These aspects are represented by graphical icons. After evaluating these symptoms the user can save the medical report by making a pinching movement with their hand (Figure 59d). Based on the user's medical record, the correct dose of medication is dispensed (Figure 59e). After dropping the Myoo pod, the system provides feedback by displaying a positive or funny message.

Theme: transformation

Unlike the Curtains prototype, Myoo demonstrates the transformation of physical content and graphical content in a concrete and commercially viable product example.

Myoo is a pill dispenser, which follows the patients medical history and dispenses the correct drug dose depending on the patient's daily medical report. First, the patient is asked to score different parameters which are graphically displayed. By scoring these parameters the patient can complete their daily medical report. After completing the daily report, a Myoo pod with pills is dispensed. During this whole routine, the graphical content, the user's physical actions, and the dispensing of the pills are harmoniously aligned. First, the patient saves their medical report by making a pinching gesture with his/her hands. The graphical content follows this gesture. Namely, the icons corresponding to all five symptoms move to the centre and shrink to smaller dots. These five small, white dots represent the pills in the Myoo pod. Once the medical report is saved, these white dots fall to the bottom of the display and disappear. The graphical icons transform into the dispensed pills. The Myoo pod with pills is dispensed and caught in the patient's hands. The transformation here can be seen as the vanishing of the graphical content combined with the appearance of the Myoo pod. By aligning the location and time of both events, it seems as if the graphical content transforms into the Myoo pod.

7.8 Experiment nine: Wato

Presentation

Wato is the result of the MSc thesis of Rob Uyttersprot, a second year master student Product Development at the University of Antwerp (RU, n.d.). Wato stands for Wayfinding Around Themepark Oscillation. Wato is an interactive system that tracks and controls the location and movement of visitors in theme parks.

A case study was developed for ZOO Antwerpen, a small zoo in the middle of Antwerp city (ZOO Antwerpen, n.d.). Different types of smart and dynamic signage are distributed over the different areas of the zoo. First, the system monitors the current situation by analysing how visitors navigate through the zoo's park and identifies the crowded areas in the park. Based on this information the system determines an optimal route for the visitors. The direction of the signage in the park is adjusted depending on the measured conditions in order to guide the visitors to the less crowded areas of the park.

Figure 60 Presentation of the Wato prototype in its environment. The signage displays an animation of the penguins in their aquarium while pointing to the aquarium of the sea lions.

This thesis presents one type of signage which is a shape-changing display (see Figure 60) that can adapt its shape and the displayed graphical content to match the measured conditions in real-time. Figure 61 shows how the display first points to the aquarium of the penguins to then change its shape to point in the direction of the aquarium of the sea lions.

Unlike the other experiments, the result of the experiment is not an interactive consumer product. The visitors do not directly interact with the displays. Instead multiple displays work together in a larger smart system.

Theme: transformation

The Wato design showcases a similar theme as the transformation theme presented in the Curtains prototype designed in experiment seven and the Myoo prototype designed in experiment eight. But instead of physical content transforming into graphical content, the Wato design demonstrates the idea of static graphical content becoming animated graphical content.

This is seen in the signage showed in Figure 61 which first points to the left in the direction of the aquarium of the penguins. At the same time the display in the centre of the signage shows an animation of the sea lions in their aquarium.

When the signage changes its shape to point to the right in the direction of the aquarium of the sea lions, the static images of the penguins and texts move into the display and become 'alive'. Or in other words, the static graphical content transforms into animated graphical content. At the same time, the sea lions displayed in the centre display, make way for the penguins that come swimming from the left side of the display. The animated sea lions become static images when they move out of the display.

A video of this routine can be viewed by scanning the QR code. The video shows how the static images and text turn into animated images and text as the arm folds together and unfolds again on the other side of the display.

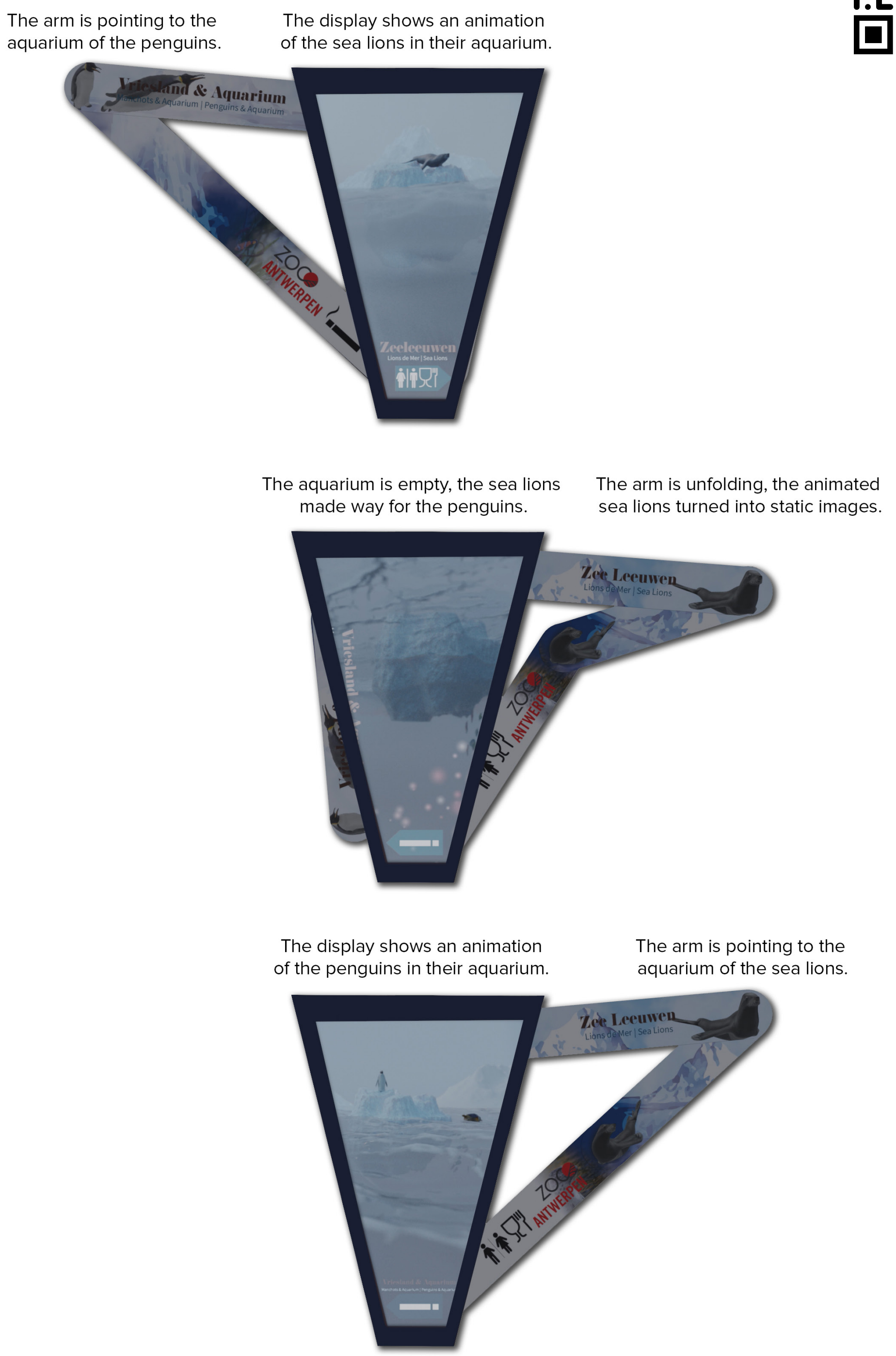

Figure 61 An example of a shape-changing display used as digital signage designed for ZOO Antwerpen. The display guides the visitors to the penguin aquarium or to the sea lion aquarium depending on how crowded these locations are.

7.9 Discussion: designing a new medium

The experiments presented in this chapter fit within the same research program as experiment five and point out additional ways to achieve synergy between physical content and graphical content (see Figure 62).

The beginning of the chapter focuses on designing a new medium for reaching the synergistic effect between physical and graphical content. Different categories of emerging display technology are discussed, that offer additional display and interaction opportunities compared to today's flat, rectangular, and rigid displays. However, most of the discussed displays are unusual and not suited to display a wide range of content, and are thus only useful for very specific applications and content. Consequently, the idea arose to develop a display that is committed to a single type of content. I call such displays Content Specific Displays. Unlike, today's flat, rectangular, and rigid displays, Content Specific Displays can reflect a physical commitment to the displayed graphical content. Content Specific Displays can provide a greater sensitivity and responsiveness to the displayed graphical content than today's generic displays. They are a condition or a medium to reach a synergistic effect between physical content and graphical content.

In total this thesis presents five examples of Content Specific Displays to illustrate three hybrid synergy themes.

The Penguin Explorer prototype designed in experiment five features a modular display. In the prototype the graphical content is approached in a very physical way. By giving physical properties to graphical content and subjecting them to the laws of the physical world, the graphical content almost become physical. Because of this, both graphical content and physical content become more indistinguishable from each other, or indeed form one whole.

The Furo prototype designed in experiment six features a curved display. The prototype demonstrates the three themes, but it mainly shows how physical content and graphical content can work together as one. Both physical content and graphical content complement one another and work together in guiding the user's actions. To appear as one, physical content and graphical content are at all times in sync and connected, which means that they need to match each other for each of their interactive aspects.

The Curtains prototype designed in experiment seven features a rectangular display with two cut-outs or slots to insert the tokens. The prototype demonstrates the 'magical' experience evoked by the transformation of physical content and graphical content. The same theme is presented in the Myoo prototype designed in experiment eight. The prototype features a round, smart mirror display. Unlike the Curtains prototype, the Myoo prototype applies the transformation theme in a commercially viable product application. The transformation theme is also employed in the Wato prototype to turn static graphical content into animated graphical content.

The idea to choose for a single-purpose or Content Specific Display seems absurd as displays are favourably used for their versatile qualities and their ability to present many sorts of graphical content in a dynamic and flexible way. Experiment five to experiment nine expose potential values of Content Specific Displays such as the beauty that stems from the impossible relationship between physical content and graphical content, the transformative experience of being confronted with oneself, the entertaining effect of static graphical content becoming 'alive', or the playfulness of physical tools transforming into digital ones.

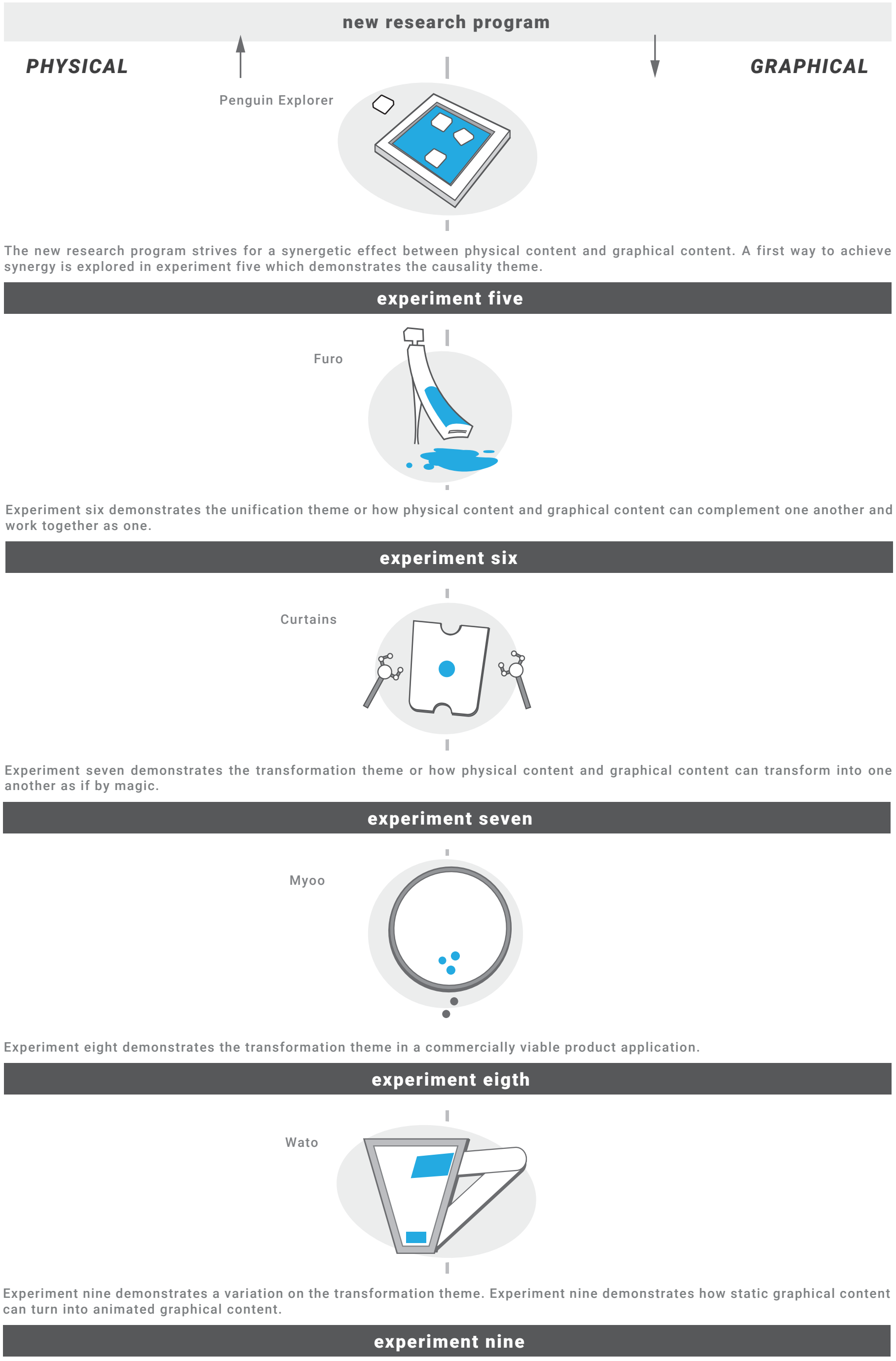

Figure 62 Evolution of the RtD process and research program.

Chapter eight: Conclusion

8.1 Introduction

This chapter presents the final research program and explains its contribution in a more general sense without explaining or elaborating the results of the experiments. The next section explains how the presented designs are embodied. Furthermore, this chapter describes the most important methodological aspects and inconsistencies of the research. Finally, this thesis is concluded by providing directions for future research.

8.2 The final research program

The final research program complies with the program described in chapter six, but is more mature and complete. The final program concerns the design of digital products and specifically focuses on the interaction design of digital products. Today, people's interaction with digital products is largely confined to the four corners of a display as, over the years, rich physical controls have increasingly been replaced by graphically-displayed digital information. However, today's generation of displays are heavily restricted by their standardized form-factor.

The research program does not encourage the use of such standardized displays and instead it promotes the use of Content Specific Displays. These Content Specific Displays make use of the variety of emerging display technology in order to offer additional display and interaction opportunities compared to the standardized displays that are currently available in the market. Content Specific Displays are tailored to a single type of content and because of that they can reflect a physical commitment to the displayed graphical content. Content Specific Displays sustain the continuous balancing act between physical content and graphical content and allow the investigation of the synergies between them.

The motivation behind the research program is based on the idea that when physical content and graphical content are together and combined in the right way, they become more than the sum or the effect produced by them separately. The research program proposes a practical framework to establish such an advantageous combination or synergy between physical content and graphical content. This framework is called the hybrid synergy framework. In total the framework suggests three different ways to achieve synergy between physical content and graphical content, which are described in the following themes

Theme: causality

The first theme aims to employ physical content and graphical content in a sort of trompe l'oeil trickery. This trompe-l'œil effect can be reached by letting the two seemingly interact on each other.

The term 'trompe-l'œil' which means to deceive the eye or fooling the eye originated in ancient Greece. It comes from this myth of the confrontation between two Greek painters, Zeuxis and Parrhasius, who were involved in a painting competition. The painter who could produce the most realistic painting would win the competition. According to the myth Zeuxis painted a likeness of grapes so natural that birds flew down to peck at them. Then his opponent, Parrhasius, brought in his painting covered in a cloth. Reaching out to lift the curtain, Zeuxis was stunned to discover that what appeared to be a cloth was actually the painting itself (Giusti, 2009).

Originally trompe-l'œil referred to the use of painting techniques to create an illusion of textured surfaces or to give three-dimensional appearances to flat canvases walls and ceilings. Today trompe-l'œil is often used in popular art to blur the line between what is real and what is not. A convincing trompe-l'œil seems very realistic, while at the same time it is impossible or not quite right.

Figure 63 shows two monumental pieces of Pierre Delavie who uses the trompe-l'œil technique in his work. The figure on the left shows this giant image located on the facade of the Palais de la Bourse in Marseille, France. The image recreates the Canebière, the historic high street in the old quarter of Marseille, which appears to be passing right through the building. An impression of depth is created by making the perspective of the scene depicted on the flat image correspond with the geometry of the building. The lines of the printed facade form an extension of the real facade and appear to form one whole. The figure on the right involves three-dimensional imagery instead of the standard two-dimensional murals. Pictures of the building in its original form are distorted and then printed on large canvases which completely hide the facade of the building. The distorted images match the building's surroundings to create this surreal setting.

The trompe-l'œil technique can be employed to amplify the synergistic effect between physical and graphical content. It does so by making the graphical content, which is currently understood as part of the digital realm and separate from the real world, uncannily real, while at the same time making the physical content, which naturally belongs to the physical world, feel almost unnatural.

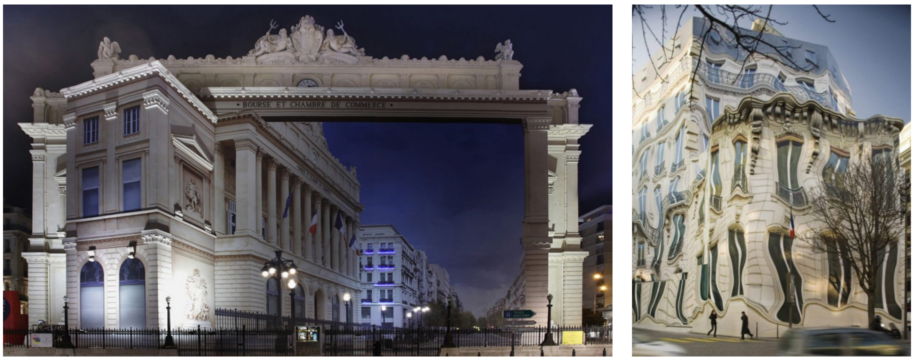

Figure 63 Pierre Delavie uses the trompe-l'œil technique is his work. Détournement de Canebière, Façade de la bourse, Marseille 2013 (left), Immeuble déformé, 39 av Georges V, Paris (right). Pictures taken from Pierre Delavie, n.d.

But how can this trompe-l'œil effect be reached? Just like painted images, digitally displayed images can mimic the properties of the physical world in order to seemingly become part of it. However, it is not enough to simply get the visual aspects such as perspective, scale, and shading of the graphical content to match the physical content. Namely, unlike static painted or printed images, digitally displayed images are dynamic and interactive. So even when the graphical content visually merge with the physical content, their 'fakeness' will become apparent very quickly, when the graphical content do not seem to be aware or affected by the physical content. Hence, in order to produce a more striking similarity between physical content and graphical content, the designer needs to create a causal relationship between them. Instead of seeing physical content and graphical content as independent entities, it can be helpful to think of them as pairs in which one member acts on the other, and the other member reacts accordingly. To establish such a causal relationship between physical and graphical content designers can follow the Newtonian logic that every action has an equal and opposite reaction. Applying this idea to the case of physical and graphical content, would mean that when graphical content interact on physical content, the physical content will be affected by it and in turn the physical content will affect the graphical content or vice versa.

So for example a physical compartment which gets filled with graphical content, will bend to the weight of the graphical content and in turn it will counteract the gravitational pull or the weight of the graphical content, preventing the graphical content to fall through it. When a graphical object hits a physical object, both will be affected by it and move in opposite directions after the collision. When a physical lid opens, the graphical content on it will slide to the side. The shifting weight of the graphical content, may cause the lid to open even further or to flip upside down.

These examples merely show that to achieve a certain degree of realism physical content and graphical content cannot be seen as independent or stand-alone entities. Instead designers can create a stronger synergetic bond between physical and graphical content by faking a causal interaction between them based on physical laws. The fact that the interaction looks real, when in fact there is no 'real' interaction gives a trompe-l'œil effect. In order to create a more convincing trompe-l'œil that seems natural to most humans, designers should respect people's intuitive understanding of the physical world. Namely, people have common sense knowledge about the physical world and naturally understand some of the basic concepts that define it. This includes concepts like gravity, friction, velocity, the persistence of objects, and relative scale. This informal human perception of basic physical principles is also called naïve physics (Jacob et al., 2008).

The same effect may not be reached when the physical and graphical content are 'dumb' and do not seem to be aware or affected by each other or when they are interactive but their behaviour does not seem to match our understanding of the physical world.

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[16] *The trompe-l'œil technique has been employed in other related and inspiring projects.*

Van Mensvoort's (2009) was inspired by the illusionary techniques used by renaissance painters to improve the physicality of the GUI, without resorting to special hardware. In his PhD he investigates if tactile effects could be evoked through an optical illusion alone. Or in other words, can a GUI simulate or fake the sensation of touch? Where the causality theme is limited to a visual illusion, van Mensvoort is interested in simulating a haptic sensation with graphical elements.

Van der Veen's (2020) research relates the art-historical procedure of trompe-l'œil to AR. He explains how trompe-l'œil and AR are not so different. They both use visual superimposition to embed images naturally into the real environment, and subtly make the natural unnatural.

Theme: unification

The second theme aims to establish synergy between physical content and graphical content by uniting them as one whole. This theme is based on the assumption that by uniting physical and graphical content in one balanced, harmonious whole, a more natural or intuitive interaction with digital products can be achieved.

We interact with most of today's digital products by performing actions in the GUI. This GUI is typically displayed on a separate display without any connection to the rest of the product. Yet, even though the different parts are co-dependent and embedded sensors allow them to cooperate, there is no visible connection between them. Arguably, a more natural interaction would be achieved if there would be.

The unification theme provides a way to bring the physical half and the graphical half of digital products together to form one whole. The idea behind the unification theme is that both halves have distinct qualities and can benefit from each other when they work together in complementary or synergistic ways.

The causality theme shows how physical and graphical content can form action – reaction pairs, here physical and graphical content are regarded as complementary partners. In order to get physical content and graphical content to work together as one, they need to be attuned to each other. They are not only visually and spatially linked with each other but to really become one they also need to match one another on each of their interactive aspects. During the interaction, physical content and graphical content are at all times in sync and connected. To achieve this, the unification aspects from the interaction frogger framework are borrowed. The interaction frogger framework presents six aspects to unite user action and product reaction: time, location, direction, dynamics, modality, and expression (Wensveen, Djajadiningrat, & Overbeeke, 2004). These six aspects are borrowed to unite physical content and graphical content.

Time: Events with physical content and events with graphical content need to coincide in time so that they are perceived as linked to each other.

Location: Physical content and graphical content should be made to fit each other's position and orientation. They form an extension of one another rather than separate parts.

Direction: The direction or movement of the physical content (up/down, clockwise/counter clockwise, right/left and towards/away) is coupled to the direction or the movement of the graphical content and vice versa.

Dynamics: The dynamics of the physical content (position, speed, acceleration, force) is coupled to the dynamics of the graphical content.

Modality: The sensory modalities of the physical content match the sensory modalities of the graphical content. This is not only limited to what is visually perceivable. The graphically displayed content may be enhanced with other modalities such as vibrations or sound.

Expression: The expression of the physical content is a reflection of the expression of the graphical content and vice versa. For example, moving the physical content faster may reflect a sense of urgency, which should be reflected in the movement of the graphical content which may move more intensely or nervously.

When both halves are in sync and effectively merged, they are not considered as separate entities. They adapt themselves to each other to become one whole. An easy way to think of it, is to consider graphical and physical content as complementary colours. Just like complementary colours, physical content and graphical content are each other's opposites and can be merged together to form a new thing.

Theme: transformation

The third theme strives to produce this almost magical, surprise effect which occurs when physical content and graphical content transform into one another.

Where the first theme looks for this trompe-l'œil effect which happens when we see an impossible scene which seems almost real, the third theme strives to obtain a similar, but different kind of effect, which is closer to the sense of wonder, mystery, and surprise response elicited by a magic trick.

Where trompe-l'œil artists strive to make something artificial seem almost natural, magicians instead use completely natural means to create effects that seem to be outside the laws of nature (Macknik et al., 2008).

Macknik et al. (2008) classified the main types of magic effects and their underlying methods. The following three are relevant to this theme.

1. Appearance: an object appears 'as if by magic'. Examples are pulling a rabbit out of a hat and the Miser's Dream (in which hundreds of coins seem to appear where previously there were none).

2. Vanish: an object disappears 'as if by magic'. Examples are vanishing of a coin and David Copperfield's vanishing of the Statue of Liberty (see Figure 64).

3. Transformation: an object changes form (size, colour, shape, weight, etc.). Examples are colour-changing card trick, Spellbound (in which a coin turns into a different coin), the Professor's Nightmare (in which three ropes of different length are made equal in length), and pigeons changing to rabbits. Transformations can be seen as the vanishing of object A combined with the appearance of object B.

Figure 64 Picture of David Copperfield who is about to make the Statue of Liberty disappear. Picture taken from Dailymotion, 2011.

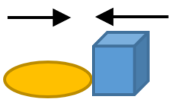
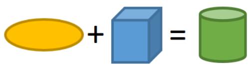
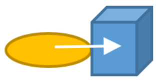
The magical effect produced by different objects transforming into one another is also found in the transformation theme. Here one object seems to lead a double life and can have two states a physical one and a graphical one. When physical content transforms into graphical content, the object in question does not just transform to another random object like changing a pigeon to a rabbit. Instead the object itself stays the same, only its characteristics are opposite. In its physical state the object is static, rigid, three-dimensional, and tangible. In its graphical state the object is dynamic, flexible, two-dimensional, and intangible.

So here physical content and graphical content are best understood as each other's twins or counterparts. The boundary of the display itself is used as a sort of transition zone or gateway. So when physical objects enter the display, their physical form is concealed behind the display and their graphical form appears. Or a graphical object can fall to the bottom of the display, and seemingly leave the display, while a physical object is being released at the point of transformation.

Physical content and graphical content can continuously transform into one another and may switch states more than once or the transformation can lead to a lasting or permanent change which cannot be reversed.

On the next page the three themes are compared to each other. Table 9 gives an overview with the three themes.

Table 9 Overview of the three themes: causality, unification, and transformation.

	causality	**unification**	**transformation**
	physical content and graphical content	physical content and graphical content	physical content and graphical content
what?	action - reaction pairs	complementary partners, colours	states, twins, or counterparts
why?	trompe-l'œil effect	a more natural interaction	magical, surprising experience
how?	Can be reached by letting physical content and graphical content seemingly interact on each other.	Can be reached by letting physical content and graphical content work together as one.	Can be reached by letting physical content and graphical content transform into one another.
principle	A interacts on B, B interacts on A 	A + B = C 	A transforms into B 
handles	Newtonian logic, basic knowledge of physical laws, naive physics.	Six unification aspects: time, location, direction, dynamics, modality, and expression.	Combining the vanishing of one object with the appearance of another one in a one-way or two-way direction.
experiment(s)*	experiment five	experiment six	experiment seven, experiment eight, experiment nine
example	In the result of experiment five the graphically-displayed penguin character pushes against the physical ice block.	In the result of experiment six the physical slider mechanism, and the liquid displayed on the reservoir work together as one.	In the result of experiment eight the graphically-displayed medical information of the patient falls to the bottom of the display and transforms into the dispensed pills.

* *The experiments are not restricted to one of the themes, they often demonstrate more than one theme. However, for every experiment only the principal or main theme is given.*

8.3 Designing an embodied alternative

To seek alternative ways to interact with digital products and to provide answers to much of the previously mentioned GUI related issues (see chapter one), this thesis looks into the field of embodied interaction. Embodied interaction describes a paradigm for HCI and is originally grounded in theoretical work on ubiquitous computing and phenomenology. The field of embodied interaction strives for interaction with digital systems that resembles people's natural way of interacting in the physical world by envisioning meaningful interaction with technology as inspired by both the physical and social phenomena of everyday life.

Over the years, the field of embodied interaction has evolved in various directions to address emerging trends in the field of HCI and to meet with new challenges and opportunities brought by the fourth wave of HCI (Bødker, 2015).

For example, embodied interaction has been employed to achieve a sense of embodiment or presence in VR applications (Debarba et al., 2017).

Embodied interaction also responded to the move towards somaesthetic design in HCI and the development of new technologies such as biosensors worn on the body (e.g., sensory augmentation used in sports (van Rheden et al., 2021)), interactive clothes, wearables, and implant technology (Fernandes, 2016; Spiel, 2021). Initially, embodied interaction has opened up a whole space of possibilities for gesture-, physical-, and body-based interaction, but despite all the work on designing for embodiment, the actual corporeal, pulsating, live, felt body has been notably absent from both theory and practical design work (as stated by Höök et al., 2015).

Furthermore, the traditional embodied interaction design principles are challenged by the variety and complexity of connected (Angelini, Mugellini, Abou Khaled, & Couture, 2018) and intelligent digital systems (Qin et al., 2019). Herath, Jochum, and Vlachos (2018) employed embodied interaction to contribute to the perception of robots as social agents. Embodied interaction is found relevant for the field of social robotics which is concerned with the development of embodied agents that can interact naturally with humans in social contexts (Lowe, 2019; Herrera Perez & Barakova, 2020).

Yet despite all these new tendencies, the presented work has been based heavily on the original concepts which were initially formulated by Dourish in 2001.

Back in 2001 the publication of the book “Where the action is” brought along a radically new way of thinking about digital technology and provided a means of overcoming the physical/digital divide. Yet, strictly speaking the field of embodied interaction is not so much concerned with opposing the physical and the digital, but is rather concerned with overcoming the underlying Cartesian mind/body split which causes the divide. Embodied interaction suggests that digital technology should not only appeal to people’s cognitive, information processing capabilities, but digital technology should also exploit other human skills and people's familiarity with the real world.

Embodied interaction is said to be a panoply of different approaches as it manifests itself in many different ways, bringing together and bridging different disciplines and approaches (Wilde et al., 2015). Tangible interaction is considered to be one of these disciplines which provides promising tools or opportunities for embodied interaction. Tangible interaction was once introduced as the new, mixed discipline, integrating the physical with the digital (Hornecker & Buur, 2006 as cited by Hummels & van Dijk, 2015). However, according to Hummels and van Dijk (2015) tangible interaction is restricted to mapping digital information onto physical representations, while not really resolving the split and fails to provide all the components required to achieve a truly embodied interaction. Embodied interaction does not only imply physical embodiment or representation of digital information, but also extends to other aspects of our everyday world such as participation in action, perception and social exchanges (Marti, 2012).

This thesis does not focus on the social component of embodied interaction.

The initial research program takes a representational stance on embodiment and plays out within a context of children’s toys. The initial research program adopts the early tangible interaction or token-based interaction approach and sets out to replace all graphically-represented digital information of games on a tablet with physical representations or tokens. However, the tokens in the presented prototypes are more than physical representations of digital information. Instead the tokens are designed as active components or building blocks of the toy which stimulate embodied activity.

First, the tokens are tangible and directly graspable and facilitate a wider repertoire of physical actions than graphical content on a display. These tokens capitalize on children’s familiarity with the manipulation of objects such as building blocks, puzzles, and other physical manipulatives. Take the token-based digital toy train prototype designed in experiment two and experiment three. Just like a traditional toy train, the prototype stimulates children's perceptual motor skills, hand-eye coordination, and dexterity. Children do not need to navigate through abstract menus, but can instead build a melody by grasping, placing, and shifting the tokens with their hands.

Second, the tokens are not detached objects, but are meaningfully embedded within the prototype and connected to the rest of the building blocks. The tokens naturally fit into the toy train track. The sections of train track are designed to hold the tokens, and afford to move a toy train vehicle over the train track to read the tokens. Playing longer melodies is reflected in longer train track constructions that can hold longer sequences of tokens. When the toy train vehicle is pushed forward faster, more tokens are read within the same time interval, increasing the tempo of the melody.

From experiment four onwards the research program moves away from a tangible and token-based interaction approach in order to give graphical content a more important role to play.

Most graphical content in a GUI is based on visual metaphors. These visual metaphors take familiar concepts from the real world to make digital information understandable to humans.

"However there is a considerable difference between using the real world as a metaphor for interaction and using it as a medium for interaction." (Dourish, 2001, p. 101)

Strictly speaking all the final prototypes include a GUI for displaying graphical content. However, in these final prototypes the graphical content is approached in a very physical, 'non-GUI' way. The graphical content functions as a medium for interaction, rather than a metaphor for interaction.

In the Furo prototype designed in experiment six, the graphically-displayed, red, liquid substance behaves almost like real water and one can interact with it as if it has real physical properties. The digital water tap acts as a sort of syringe and can be used to suck the displayed red, liquid substance from the platform into the reservoir.

The Curtains prototype demonstrates how one can physically interact with graphical content by bringing physical tools behind a display.

The interaction with the Myoo prototype is based on physical gestures and actions. The patient uses his/her hands to physically interact with the graphical content displayed on the product's display.

All these interactions go beyond interpreting and tapping on visual metaphors. The graphical content is meaningfully displayed and is used to guide physical action.

8.4 Methodological aspects of the research

The evolving and transitional nature of the research

This research employs an evolving approach to RtD, according to the program/experiment dialectics approach described by Redström (2011) which is commonly referred to as programmatic design research. The programmatic design research approach comprises two main components: a research program and experiments. Rather than starting from a fixed and predetermined research program, the research program is influenced and challenged by the experiments and changes along the way.

Insights gained from the experiments can be used to either incrementally refine or drastically change the research program. In this research, the direction of the research program significantly changed along the way. Because of this, a new research program was needed halfway the process. Where the initial research program sets out to replace all graphical content with physical ones, the final research program instead recognizes the added value of graphical content and shifts its focus to establish an advantageous combination or synergy between physical content and graphical content.

The approach taken recognizes that new research opportunities can be found through the practice of wandering and is receptive and open to what might emerge from the experiments. This practice is also called drifting. According to Krogh and Koskinen (2020) drifting are those actions that take design away from its original brief or question and which lead to a result that was not anticipated in the beginning. In programmatic design research, drifting should not be seen as something accidental, but it is an intentional process that “allows us to articulate ideas we might have developed in the practical experiments, but that are not explicit in the actual program” (Redström, 2011).

According to Krogh and Koskinen, drifting can be used in various ways depending on the epistemic standards that are used. For example, in experiential design research the design artifact itself determines the direction of the research and becomes the key motivator for drifting (Ibid). In methodic or constructive design research a more rational, controlled approach to drifting is followed. Any act of drifting has to be justified and is based on explicit evidence (Ibid). In this thesis a programmatic approach is followed. Drifting occurs to some extent in the design work. However, the new opportunities the designs point to are developed further and conceptualized in the research program. The designs are used to spark and concretize new ideas and concepts, which are in turn needed to understand the design work.

In programmatic design research the process of drifting is not as straightforward and objective as the controlled drifting in methodic or constructive design research. Neither is it based merely on personal experiences. Instead, the chosen research direction is outlined with the necessary conceptual knowledge. The initial research program, for example, reuses the concepts of tangible and token-based interaction. For the development of the new research program the concept of coupling and specifically the interaction frogger framework and aesthetics of coupling framework are used.

Research program vs educational program

Next to research programs, academia has to deliver educational programs. As a research group we build a foundation for the educational program. Educational programs are oriented towards developing skills in students to prepare them for professional practice, often with a degree as the final outcome.

In this thesis, the research program is implemented within the educational program of the bachelor and master of the Product Development degree at the University of Antwerp. The research program provides a conceptual foundation for the educational program. The research program has particularly influenced the User Experience (UX) and Interaction Design (IxD) project, respectively taught at the third and fourth year.

In this year's UX assignment, special attention is paid to the harmonious coming together of physical movements and on-screen movements (taken from the course’s text and lecture notes 2021-2022).

Last year's IxD assignment focused on the development of demonstrators of Content Specific Displays and was directly linked to the subject of the research program. The briefing states: "Marieke combines physical shape changes with on-screen content. Hypothesis: What happens when a shape-changing display [17] is designed for one specific on-screen content?" The three themes are presented. However, the briefing of the IxD projects describes a preliminary version of the research program. The themes were not final yet and were named: naive physics, hybrid affordance, and transformation (taken from the course's project briefing 2020-2021). The videos included in this thesis are presented to the students as inspiration. The students are asked to develop a prototype of a Content Specific Display. The design needs to embody at least one of the presented themes. The prototypes are used as demonstrators. The students are asked to make a video of the interaction routine with their prototype.

The inter-relation between the research program and the educational program is not a one-way relation. Instead both influence and support each other. The implementation of student work has supported the research program in different ways.

First, student projects allow the exploration of vague or immature research ideas in a quicker and shorter time frame. Because of this, different subjects for student projects were proposed to explore potential research directions when there was no room, time, or budget available to carry out the experiment within the PhD project. Second, as a tutor/researcher you keep an overview on the program, without getting lost in the details of the design project or the development of a prototype. Third, the different student projects allowed to further develop and refine the research program. Especially the second phase, which forms the main contribution of the PhD, relies on explorations carried out by students. Fourth, you can choose to outsource the parts which fall outside the core focus and scope of the research program to students. The research uses children's toys as a case study. Experiment one to experiment five are all examples of children's toys. The results of the students enabled to extend the research program to other product applications.

It goes without saying that only a careful selection of student results were used. The student results had to meet the following selection criteria to be included in the thesis:

1. The result has to fit within the research program or has led to an important development within the RtD trajectory. The result is essential for

understanding the narrative presented in the thesis. Other side-projects which were carried out under my supervision are often related but are not included in the thesis.

2. The quality of the deliverables is strong. The design result is richly documented with high-quality renders, videos, or pictures. In some cases the visual material was insufficient and therefore new material was developed afterwards or retouched, so that the result could be added to the thesis.

3. The result has to show a strong, well-thought out, and clear example of the intended interaction. Potential yet incomplete or inconclusive ideas are not included in the thesis.

4. Only results of master students are included. Master students have a greater skill-set and more experience on the topic compared to bachelor students which only followed the UX course, which is the introductory course for the Designing for Interaction program for the master of Product Development degree at the University of Antwerp. Four of the five student projects that are included in this thesis, are master thesis projects. This is because master thesis projects are larger projects that span almost a full year, and they often are carried out in the form of design research projects.

5. Permission was granted to use the result.

Not all these students have worked under my supervision. Only experiment four (Fix the Shuttle) and experiment seven (Curtains) were conducted under my supervision. These particular cases are the result of two MSc thesis projects which I have initiated. The scope of these theses directly stem from this PhD research. The result of experiment nine (Wato) was inspired by the research program and by the results presented in experiment seven. Experiment six (Furo) and experiment eight (Myoo) were not carried out under my supervision. The latter two results were added to this thesis, because they provide clear examples of the concepts described in the research program.

Lab vs showroom

Within RtD there are three different approaches or traditions to be followed referred to as the lab, the field, and the showroom approach (Koskinen et al., 2011). This research combines a more formal RtD lab approach and a less formal RtD showroom approach.

The lab approach enabled to evaluate different types of interactions with children and to determine their preferences to guide the development of design recommendations for subsequent prototypes. In these experiments functional prototypes are developed that can be tested with the user. Statistical methods and empirical methods for user evaluation of related scientific disciplines are adopted to provide a more objective approach for making design decisions. All user evaluations are conducted within a school context, yet, these evaluations are considered as lab studies and not as field studies. Namely, the experiments are conducted in a controlled way. The tests were conducted in a school just because there are many children, it might as well have happened in a lab.

The other experiments follow a showroom approach. The showroom approach builds on art and design rather than on science (Koskinen et al., 2011). The showroom approach positions itself against the traditional scientific standards in order to give the designer more freedom to explore and develop a conceptual framework. The prototypes developed in these experiments are not used as tools for testing, but are merely intended to demonstrate new ideas. In this thesis, the showroom experiments rely on video prototyping [18]. Videos can be used to capture and present an idea or a concept that might be difficult to prototype otherwise.

Abstract explorations vs concrete use cases

To explore the synergies between physical content and graphical content often abstract examples of interactions are used without a specific use case. This is seen in experiment six and experiment seven. While, in experiment five, experiment eight, and experiment nine, new interactions are realized within a specific context of use.

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[17] This was the original starting point before other kinds of display technology were explored. After an extensive literature search it became clear that there are many prototyped examples of emerging display technology which do not fit within the field of shape-changing displays. For example, non-rigid displays such as deformable and malleable displays are considered as a different category.

[18] Many other studies have reported on the usefulness of video for exploring and communicating ideas in the field of interaction design such as: Arnall & Martinussen, 2010; Arnall, 2014; Bardzell et al., 2016; Bonanni & Ishii, 2009; Briggs et al., 2012; Halskov & Nielsen, 2006; Kinsley, 2010; Markopoulos, 2016; McKay, Scott, Histon, & Torenvliet, 2011; Raijmakers, Gaver, & Bishay, 2006; Vistisen, 2016.

According to van Dijk, Moussette, Kuenen, and Hummels (2013) the first way of working is often used within computer science and engineering-based interaction design research, whereas the latter way of working is typical for industrial design. Van Dijk is particularly critical about the first approach which would lead to the development of 'cool new technology' rather than useful end-products (Ibid).

In this thesis both approaches are used to explore new interaction possibilities, so it is able to compare them.

One of the advantages of having a use case is that it gives the designer something to work with, it provides the content needed for the development of new interactions. Furthermore, industrial designers are trained to find creative solutions for conflicting user needs such as low-cost and high-performance or light-weight and robustness. These conflicts stimulate the creativity of designers, resulting in solutions which may otherwise not be thought of.

However, often the use case drives the design. Potential interaction possibilities may be ignored when they do not fit the intended use of the product. More abstract explorations of interactions allow designers to concentrate on the interaction design. Furthermore, different interactions can be more easily compared when they have the same abstract form. This is for example seen in the study conducted by Kwak, Hornbæk, Markopoulos, and Bruns (2014). A variety or a collection of shape-changing interfaces are designed as one set consisting of six abstract artefacts in order to discuss the design space of shape-changing interfaces more generally (Ibid).

Interactions which are explored first in a more general sense, can later prove their usefulness within a specific product application. For example, the Curtains prototype in experiment seven demonstrates the transformation theme without considering product use. In experiment eight, the same theme is used within a clear product example.

8.5 Future research

While investigating, new challenges and opportunities emerged. This section describes six possible directions for future research.

1. This thesis investigates the relationship between physical content and graphical content in designing digital products. The thesis describes three different ways to achieve synergy between physical content and graphical content and demonstrates these with prototyped examples of digital products. I invite other researchers to expand this understanding further. The three themes (causality, unification, and transformation) can be applied to different product cases or can be understood in new ways or even new themes may arise in carrying out future studies.

2. The concepts of this thesis are not only applicable to the design of digital products, but are also relevant for other applications which are related, but outside the scope of this thesis such as immersive displays, AR-based applications, and interactive environments.

   The framework presented in this thesis can be useful for designing immersive, one-of-a-kind displays used for advertising and entertainment purposes. How can a synergy between the physical display surface and the displayed graphical content lead to the development of advertising displays and billboards that are more captivating and effective in grabbing the passer-by's attention than regular displays?

   The themes investigated in this thesis can also be applied to AR-based HMD and HUD that augment the real world scene with visual information. The hybrid synergy themes investigated in this thesis can help designers in mapping the computer generated graphical layer onto the physical environment in a meaningful way. This is especially relevant for cases where the physical scene or set-up and the augmented layer with graphical content can be designed in parallel.

   Next to digital products, the framework can also be applied in designing interactive environments and interiors. What happens to the established synergy when the graphical content is not presented in a fixed location and always available, but it instead adapts itself to the situation and can move between different connected components in the physical space?

3. The prototypes presented in the final experiments are merely used to demonstrate examples of Content Specific Displays. To develop user-ready prototypes of such one-off display designs some technical issues and challenges need to be resolved. Further technological improvements are required to ensure the adoption of the display technologies that are found in literature. Furthermore, the prototypes in this thesis challenge current knowledge of content development. New content designs should be fully responsive to all possible variations in shape. This may constraint the range of possible new forms. Displaying 2D content on 3D dynamic shapes can lead to deformations as well as incomplete alignment. New software packages and hardware tools are required to deal with these new challenges. Furthermore, the effect of nonplanar display surfaces on human perception and performance needs further attention. These issues need to be resolved in order to turn the ideas presented in this thesis into reality.

4. How does the hybrid synergy framework need to be used, if at all, when designing connected and intelligent products? Can the generic content from your smartwatch simply flow into the Content Specific Display of a connected digital product or does it need to adapt itself in order not to lose the intended synergistic effect? And what with intelligent products that are capable of learning? I invite other researchers to explore how the framework can be extended to deal with the complexities of such connected and intelligent products.

5. The feasibility of the concepts of this thesis in real product applications does not only depend on technical aspects. It is important to understand future user needs and preferences. This remains challenging as users are not yet familiar with the use of Content Specific Displays due to the absence of similar examples in the market. Future studies in this area can help to reveal potential use cases where highly specialized displays would be desirable.

6. This thesis illustrates and explores a particular kind of RtD, one which acknowledges the evolving and transitional character of RtD. This approach to RtD is especially useful for flexible, open-ended research projects, where the scope is not yet-well developed at the start of the project. Future studies are needed to further test the potential, limitations, and applicability of this method.

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Appendices

Appendix one:

Empirical data obtained from user evaluation experiment two

The empirical data obtained from experiment two is available at https://github.com/mariekevancamp/user-evaluation

The document contains the results from all the 34 user tests of the user evaluation. These results include both the This-or-That ranking and the data from the Laddering interview with transcriptions of the responses of the participants and the resulting ladders (chains of attributes, consequences and value). The transcriptions only include the participant's responses to the This-or-That and Laddering questions. The rest of the conversation between the facilitator and the participant that was recorded, is not transcribed here. However, the full conversations and the observations from the user study, plus the patterns of answers for all the different interviews, helped to interpret the participant's responses and form ladders. The videos are not attached in the thesis for ethical reasons.

Appendix two:

Statistical output obtained for experiment two

This appendix contains the statistical tables for experiment two with A = traditional toy train, B = digital toy train, C = game on a tablet. The tables summarize the results from the statistical test (Friedman test and Wilcoxon Signed Rank tests) performed in IBM SPSS Statistics V27.

Friedman Test

Ranks

	Mean Rank
A	1,65
B	1,97
C	2,38

Test Statistics[a]

N	34
Chi-Square	9,235
df	2
Asymp. Sig.	,010

a. Friedman Test

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
B - A	Negative Ranks	13[a]	17,54	228,00
	Positive Ranks	21[b]	17,48	367,00
	Ties	0[c]		
	Total	34		

a. B < A
b. B > A
c. B = A

Test Statistics[a]

	B - A
Z	-1,232[b]
Asymp. Sig. (2-tailed)	,218

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
C - B	Negative Ranks	12[a]	15,50	186,00
	Positive Ranks	22[b]	18,59	409,00
	Ties	0[c]		
	Total	34		

a. C < B
b. C > B
c. C = B

Test Statistics[a]

	C - B
Z	-2,086[b]
Asymp. Sig. (2-tailed)	,037

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
C - A	Negative Ranks	9[a]	16,56	149,00
	Positive Ranks	25[b]	17,84	446,00
	Ties	0[c]		
	Total	34		

a. C < A
b. C > A
c. C = A

Test Statistics[a]

	C - A
Z	-2,618[b]
Asymp. Sig. (2-tailed)	,009

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

Appendix three:

Empirical data obtained from user evaluation experiment three

The empirical data obtained from experiment two is available at
https://github.com/mariekevancamp/user-evaluation

The document contains the results from all the 44 user tests of the user evaluation. These results include both the This-or-That ranking and the data from the Laddering interview with transcriptions of the responses of the participants and the resulting ladders (chains of attributes, consequences and value). The transcriptions only include the participant's responses to the This-or-That and Laddering questions. The rest of the conversation between the facilitator and the participant that was recorded, is not transcribed here. However, the full conversations and the observations from the user study, plus the patterns of answers for all the different interviews, helped to interpret the participant's responses and form ladders. The videos are not attached in the thesis for ethical reasons. Furthermore, the participant's choices for a motorized or manual vehicle are also included.

Appendix four:

Statistical output obtained for experiment three

This appendix contains the statistical tables for experiment three with A = tokens, B = graphical application. The tables summarize the results from the statistical test (Analyze Mean Score and Wilcoxon Signed Rank test) performed in IBM SPSS Statistics V27.

Case Processing Summary

	Cases					
	Included		Excluded		Total	
	N	Percent	N	Percent	N	Percent
A	43	97,7%	1	2,3%	44	100,0%
B	43	97,7%	1	2,3%	44	100,0%

Report

	A	B
Mean	1,72	1,28
N	43	43
Std. Deviation	,454	,454

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
A - B	Negative Ranks	12[a]	22,00	264,00
	Positive Ranks	31[b]	22,00	682,00
	Ties	0[c]		
	Total	43		

a. A < B

b. A > B

c. A = B

Test Statistics[a]

	A - B
Z	-2,897[b]
Asymp. Sig. (2-tailed)	,004

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

List of abbreviations

ACM	Association for Computing Machinery
AR	Augmented Reality
CAD	Computer Aided Design
CNC	Computer Numerical Control
DAW	Digital Audio Workstations
EPS	European Project Semester
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HMD	Head Mounted Display
HUD	Head Up Display
HUI	Hybrid User Interface
HRI	Human-Robot Interaction
ICT	Information Communications Technology
IoT	Internet of Things
IxD	Interaction Design
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MDF	Medium Density Fireboard
MIDI	Musical Instrument Digital Interface
PANAS	Positive Affect Negative Affect Schedule
RPM	Revolutions Per Minute
RtD	Research through Design
SAM	Self-Assessment Manikin
STEM	Science, Technology, Engineering, and Mathematics
TUI	Tangible User Interface
UX	User Experience
VR	Virtual Reality
WIMP	Windows Icons Menus Pointer

Index

EMBODIED INTERACTION IN A WORLD FULL OF DISPLAYS

Doctoral dissertation submitted in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) in Product Development by

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Antwerp, 2022

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