Introducing the Internet of Things in classrooms through discovery-based learning and physical computing

Susan (Zuzanna) Lechelt

Department of Computer Science
University College London

This thesis is submitted in fulfilment of the requirements for the degree of **Doctor of Philosophy** in **Human-Computer Interaction**

November 2019

DECLARATION

I, Zuzanna Lechelt confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed,

ABSTRACT

Interest in teaching children about computing is increasing apace, as evidenced by the recent redesign of the English computing curriculum, as well as the variety of new tools for learning about computing by making, tinkering and coding. The rapid emergence of the Internet of Things (IoT), through which billions of everyday objects are becoming embedded with the abilities to sense their environment, compute data, and wirelessly connect to other devices, introduces new topics to the scope of computing education. However, what these IoT topics are and how they can be taught to children is still ill defined. Simultaneously, new handheld and tangible physical computing toolkits offer much promise for promoting collaborative, discovery-based learning within classroom settings. These toolkits provide new opportunities for learning about electronics and IoT, by enabling children to connect the digital with the physical. This thesis investigates how IoT topics can be introduced to primary and secondary classrooms through discovery-based learning together with a physical computing toolkit.

Specifically, this research addresses three core questions. First, what IoT concepts and topics are appropriate for children to learn about? Second, how can discovery-based learning be designed to facilitate IoT learning for beginners? Third, how can learning about IoT be made accessible and inclusive? This thesis describes the design and evaluation of novel learning approaches for teaching children about introductory IoT topics, especially understanding sensors, actuators and data, as well as critical thinking about their limitations and implications. The contribution is to provide a detailed,

descriptive account of how children can first learn these topics in classroom settings through discovery-based activities, as well as of how discovery-based activities together with new types of tangible, physical computing interfaces can contribute to engagement, curiosity and collaborative interaction in computing classrooms and beyond.

IMPACT STATEMENT

The pedagogical insights, frameworks and design implications derived from this research are seen as having a strong impact for academia, industry and pedagogical practice. Digital fluency is one of the key skills for the 21st century and best practices for teaching digital fluency to children are constantly evolving, with much empirical focus being placed on teaching coding and making. However, given that new technology paradigms are evolving apace, this thesis takes the perspective that being able to engage in more general *higher level thinking* about a technology is equally important to being able to *construct objects* with technology.

In light of this, this thesis contributes a new framing of digital fluency to the domain of computing education, which highlights the central importance of teaching children how to analyze, evaluate and think critically about new technologies and their limitations. This framing is seen as being useful for researchers and engineers developing new toolkits for teaching computing, that flexibly support learning by mixing discovery, making and coding - rather than just focusing on one of these approaches.

The approach adopted in this research of promoting discovery learning with a tangible interface was found to promote curiosity, playfulness and reflection on abstract IoT concepts. Thus, the thesis provides evidence of how IoT can be successfully introduced to children in practice. The empirical findings also contribute broader design implications for teaching computing in real classrooms. These comprise suggestions for enabling children to learn from their peers, and for ensuring that children receive appropriate guidance as they learn when constant, individualized guidance is not possible. The findings emphasize that the way children interact with a technology can fundamentally change, based on the socio-material context in which they are learning. Thus, the contributions also complement and extend previous work on learning approaches with tangible toolkits within Human Computer Interaction (HCI), which are often tested in informal environments or lab settings.

The thesis also contributes design considerations for ensuring computing education is more inclusive, by making learning accessible and engaging for a diversity of learners, rather than those traditionally best positioned to engage with computing. Specifically, the findings suggest how to ensure a learning approach is accessible to children with cognitive disabilities, as well as how to make the approach personally meaningful, in order to make computing appealing to all genders.

The methodology adopted in the thesis highlights the importance of studying the *learning process* when evaluating a technology, rather than just the *learning outcome*. Therefore, the thesis hopes to inspire future work in HCI that places a stronger empirical focus on how tangible toolkits influence learning as a process, in addition to studying how they change learning outcomes.

The iCASE studentship which enabled this research was partially funded by the BBC. This supported broader impact in terms of enabling collaboration between industry and academia – by providing opportunities to engage in co-design and ideation with

BBC researchers. It also opened many doors to demonstrating the work at outreach events with wide audiences, like BBC festivals and events for children.

ACKNOWLEDGEMENTS

Foremost, I would like to thank my UCL supervisors, Yvonne Rogers and Nicolai Marquardt – you are both sources of constant inspiration and it has been a true honour to work with you. Yvonne, thank you for your constant faith in me and for always encouraging me to take every opportunity to pursue my research interests. Your mentorship has shaped the way I think about research and beyond, and your voice, always probing me to ask "why?" will doubtlessly be present in my mind throughout my career. Nic, your positivity is infectious; thank you for always providing an insightful, fresh perspective when I have been in doubt, as well as for helping me discover a passion for making and tinkering.

Funding for this PhD was provided by the EPSRC and BBC through an iCASE studentship. This has also given me the opportunity to work with BBC R&D throughout the past four years. To my BBC mentors Phil Stenton and Mike Evans, as well as all the others from BBC with whom I have had the opportunity to work - thank you so much for always making me feel welcome in MediaCity and for involving me in your research, even beyond the scope of my thesis. Learning about the intersection of academia and industry has been a fantastic experience.

Of course, this thesis would not have been possible without the numerous people who have enabled the many classroom and outreach events I had the pleasure to run as part of the research. To the fantastic Venus Shum, Nicola Yuill, Lena Nagl and Grazia Ragone – I'm so grateful to have had the opportunity to collaborate with you. To the wonderful Elpida Makrygianni – your passion for what you do is always inspiring – it has been brilliant working with you. Thank you to the countless teachers and even more countless students for allowing me to invade your classrooms with an open mind, and to the museums and festivals that have allowed me to exhibit this work. And thank you to the wonderful UCL students who have assisted the sessions!

I cannot imagine the past four years at a place other than UCLIC; the open, kind and supportive students, faculty, and administrative and support staff make it a truly special research group. I am forever grateful to my colleagues for the continuous uplifting chats, donut-fuelled pomodoros, hacking sessions, outlandish side projects, evenings in the pub and ukulele nights. You have made my time at UCL.

To my dear friends outwith PhD life – thanks for always keeping me smiling and grounded. Finally, and most importantly, thank you to my family. To my mama - a proper thank you would surely be longer than this thesis; thank you for supporting me and being on my side, always. To my brother - all of my best life decisions can be traced back to you. And of course, to my exceptional grandma, Marianna Michalska:

Moja ukochana Babciu, tę pracę dedykuję Tobie!

PUBLICATIONS AND AWARDS

The following publications are related to this thesis:

[7] Lechelt, Z., Rogers, Y., Marquardt, N. (2020). Coming to Your Senses: Promoting Critical Thinking about Sensors through Playful Interaction in Classrooms. In *Proceedings of the 19th International Conference on Interaction Design and Children.* ACM.

Overview: *This publication presents the findings from a school study investigating how critical thinking about sensors and the act of sensing can best be taught to children. It is the basis of* ***Chapter 8*** *in this thesis.*

[6] **Lechelt, Z.**, Rogers, Y., Marquardt, N. (2019). How Embodied Interactions Manifest Themselves During Collaborative Learning in Classroom Settings. In *Proceedings of CSCL.* International Society of the Learning Sciences.

Overview: *This publication presents an overview of the findings from the first school study carried out during this PhD, which are presented in* ***Chapter 7****.*

[5] **Lechelt, Z.**, Rogers, Y., Yuill, N., Nagl, L., Ragone, G., & Marquardt, N. (2018). Inclusive computing in special needs classrooms: designing for all. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (p. 517). ACM.

Overview: *This CHI paper presents the findings from a Special Education Needs school study, and is the basis of* ***Chapter 9*** *in this thesis.*

[4] Rogers, Y., Shum, V., Marquardt, N., **Lechelt, Z.**, Johnson, R., Baker, H., & Davies, M. (2017). From the bbc micro to micro: bit and beyond: a british innovation. *interactions*, *24*(2), 74-77.

Overview: *This Interactions article discusses the collaboration between BBC and UCL during this research. It also provides an overview of the motivations for using the Magic Cubes in schools, and the key observations from initial deployments of the toolkit. It is referenced in* ***Chapter 6*** *when describing the design of the Magic Cubes.*

[3] Rogers, Y., **Lechelt, Z.**, Marquardt, N., Shum, V. (2016). Digital fluency: the next big thing beyond coding. In IET Partner News, 31.

Overview: *This scientific magazine article discusses our conceptualization of digital fluency, and proposes the types of learning activities that might support its development. The connection between the research undertaken in this PhD and the broader idea of digital fluency is expanded on at length in* ***Chapter 11****.*

[2] **Lechelt, Z.**, Rogers, Y., Marquardt, N., & Shum, V. (2016). Democratizing children's engagement with the internet of things through ConnectUs. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct* (pp. 133-136). ACM.

***Overview**: This extended abstract describes the initial ideation phase of planning workshops to teach children about IoT using the Magic Cubes.*

[1] **Lechelt, Z.**, Rogers, Y., Marquardt, N., & Shum, V. (2016). ConnectUs: A new toolkit for teaching about the Internet of Things. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 3711-3714). ACM.

***Overview:** This CHI demo showcased the initial discovery-based tasks designed for the Magic Cubes. These are presented in detail in **Chapter 6**.*

The following publications are unrelated to this thesis, but were published during this PhD:

[12] **Lechelt, Z.**, Elsden, C., Helgason, I., Panneels, I., Smyth, M., Speed, C., and Terras, M. (2019). How Can We Balance Research, Participation and Innovation as HCI Researchers? In *Proceedings of the Halfway to the Future Symposium 2019*.

[11] Wright, C., Allnut, J., Campbell, R., Evans, M., Forman, R., Gibson, J., Jolly, S., Kerlin, L., **Lechelt., Z.**, Phillipson, G., and Shotton, M. (2018). AI in Production: Video Analysis and machine learning for expanded live events coverage. In *IBC 2018*.

[10] Schulte, B. F., **Lechelt, Z.**, & Singh, A. (2018). Giving up Control – A Speculative Air Pollution Mask to Reflect on Autonomy and Technology Design. In *Conference on Designing Interactive Systems (Companion Volume)* (pp. 177-181). ACM.

[9] Angelini, L., **Lechelt, Z.**, Hornecker, E., Marshall, P., Liu, C., Brereton, M., ... & Mugellini, E. (2018). Internet of Tangible Things: Workshop on Tangible Interaction with the Internet of Things. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (p. W14). ACM.

[8] Di Cuia, D., Janovica, J., **Lechelt, Z.**, Li, S., & Purewal, H. (2016). CarryLine: A Tool for Management and Rehabilitation of Post-Natal Chronic Back Pain. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 26-31). ACM.

Awards:

- UCL Provost's Award for Engineering Engagement (2017)
- Best Conference Paper Award (Publication [11])
- Finalist in Student Design Competition (for publication [8])

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The rapid technological advances of the 21st century have led to a global society in which technology permeates virtually all aspects of day-to-day life. Given this, fostering a literate and engaged society involves teaching children not only to use contemporary technology, but also to understand how it works and engage with it critically and creatively. This has been highlighted by numerous government and industry reports (e.g., [Computing At School Working Group, 2009; Pearson & Young, 2002; Quinlan, 2015]), which have called for an increased emphasis on hands-on coding, tinkering and making with technology in primary and secondary education. A main goal of these calls for reform of computing education has been described as digital fluency [Resnick, 2002]. The notion of digital fluency aims to drive children's interest in computer science and engineering, and to go beyond teaching children how to use technology. Its key goal is instead to instill a skillset that enables children to reason about how technology works, how it can be used to innovate and solve problems, and how to think critically about the societal implications of emerging technologies (e.g., [Sparrow, 2018])

Interest in best practices for teaching digital fluency is rapidly increasing, as evidenced by both curricular changes and grassroots movements. From the redesign of the English computing curriculum which now emphasizes computational thinking and creativity rather than learning to use existing software [UK Department of Education, 2016], to the rise of the maker movement [Blikstein, 2013], and the advent of an array of commercial toolkits for making, tinkering, and coding (e.g., [Arduino, n.d.; Bdeir, 2009; Micro:bit, n.d.]), many children now have more opportunities to create with technology, in the classroom and beyond. To date, much research has been carried out to inform best practices for enabling children to tinker with hardware, learn to program and engage with computational thinking. However, other aspects of digital fluency have so far received relatively less empirical attention; these include the ability to understand the underlying principles of technologies and to think critically about the limitations and implications of technologies. The goal of this thesis is to investigate how these aspects of digital fluency can be introduced to learners, in a way that is engaging, playful and inspires curiosity.

In particular, this research investigates new approaches to teaching digital fluency through focusing on one growing area: what has been termed the "second digital revolution" [UK Government Office for Science, 2014], namely, the Internet of Things (IoT), through which everyday objects are becoming embedded with the abilities to sense their environment, compute data and wirelessly connect to other devices. Industry experts correctly forecasted that by 2020, nearly 50 billion physical objects would be connected to the Internet [Cisco Systems, 2013]. The emerging ubiquity of connected devices indicates that the fundamental computational topics underlying IoT technologies are central for the next generation of engineers, computer scientists and designers. The question this raises is, *what does digital fluency mean in the context of IoT?* In particular, IoT introduces to digital fluency new topics related to understanding and critically reflecting on the functionality of hardware, the nature of data and even the societal implications of a world where sensing and connectivity are ubiquitous. These topics are still largely absent in the primary and secondary computing curriculum, and taught mainly only in specialized higher education. Little research exists about specifying how IoT fits into the broader notion of digital fluency, or about best-practice pedagogical approaches for teaching about IoT.

At the same time, the decreasing costs and miniaturization of hardware have in recent years enabled researchers and engineers to invent a diversity of new forms of hardware to augment children's learning experiences. These include physical and tangible interfaces – which have taken the forms of playful, interactive storytelling objects, blocks and robots (e.g., [Frei, Su, Mikhak, & Ishii, 2000; Price & Rogers, 2004; Zuckerman, Arida, & Resnick, 2005]). Tangible interfaces have potential for lowering the entry threshold to learning about complex and abstract concepts, by rooting learning experiences in the physical world (e.g., [Marshall, 2007]). They also have much potential for supporting a pedagogical approach known as discovery learning – that is, learning through self-guided exploration – which can be engaging, playful, and bring complex concepts to a level appropriate for younger children (e.g., [Price & Falcão, 2011]).

Following on from this approach, the research presented in this thesis investigates whether the coupling of tangible interfaces with discovery learning is beneficial for teaching children about IoT. Specifically, the research begins by mapping out the conceptual space of IoT topics that may be appropriate for children to learn about. Subsequently, through a process of design and evaluation, it addresses whether and how playful, discovery-based experiences with a tangible interface can promote children's curiosity about IoT, enable them to critically reflect about IoT technologies, and spark interest in further learning. Moreover, the research explores whether and how children can learn abstract IoT concepts through interacting with these kinds of tangible interfaces, by being able to experience and make connections between sensing aspects of the environment and how they cause different kinds of digital effects in an interface. Through this process, as the work progresses, links are also made between potential discovery learning methods and existing and envisioned computing curricula for schools.

A central value adopted in this thesis was to introduce IoT concepts to all school children, regardless of their ability or whether learning in a classroom or informal setting. This was done by investigating how to make the learning experience appealing, understandable and relevant to children aged 8 years upwards at and outside of school, and for those with special needs.

1.1 Overarching Research Questions

The research reported in this thesis investigates how to introduce the first steps of learning about IoT. It focuses primarily on investigating how discovery learning, together with a physical computing toolkit, can be designed for teaching IoT topics at an appropriate level for 8-12 year old children, as well as 16-19 year old teenagers with special education needs, while simultaneously fostering an engaging and collaborative learning experience. In particular, it seeks to address this by answering the following three overarching research questions.

1.1.1 What IoT topics are appropriate to teach to children?

The IoT, alongside other emerging technologies, is rapidly changing what the next generation needs to know about computing. However, while there is emerging research on what IoT topics are appropriate for specialized, higher education (e.g., [Burd et al., 2018; Kortuem, Bandara, Smith, Richards, & Petre, 2012]), it is still unclear what children just starting to learn about computing need to know about IoT. This thesis addresses this gap by mapping out what IoT topics are relevant for children just starting to learn about computing, especially those who are 8-12 years old.

1.1.2 Can IoT topics be taught through discovery-based learning? If so, how?

A discovery-based learning process, when coupled with appropriate instructional guidance, has been suggested to enable learners to engage with learning material at a deeper level than through explicit instruction [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011]. Furthermore, learning through discovery can often promote high levels of playfulness and sustained engagement [Price & Falcão, 2011; Rogers et al., 2002]. The question this raises, is how the benefits of discovery learning can be leveraged to teach IoT topics to children? Specifically, can discovery learning help make complex IoT topics easier to understand, as well as help children to critically reflect on the limitations of IoT technologies? The research reported in this thesis couples a discovery learning approach with a customized tangible interface – i.e., physical-digital cubes called the Magic Cubes – to investigate how self-guided inquiry can lead children to understand and reflect on IoT topics. It also investigates the roles of embodied interaction, collaborative learning, and appropriate instructional guidance, in successful discovery learning.

1.1.3 How can teaching IoT be made more inclusive?

The topic of how approaches to learning about computing can be designed to be inclusive is still in its infancy. While recent work has investigated how computing education can be made accessible to children who are visually impaired [Thieme, Morrison, Villar, Grayson, & Lindley, 2017], as well as instructional strategies adopted by computing clubs for individuals with cognitive disabilities [Koushik & Kane, 2019], there is still little research about whether and how approaches initially designed with children in mainstream classrooms in mind can be carried over to children in special education needs classrooms. A focus of this research is to address this, by extending the discovery learning approaches designed to suit a special education needs school context.

By addressing these three overarching questions, this thesis contributes theoretically and empirically to the wider body of work on computing education and interaction design for children. It also highlights the central role of interaction design when developing new learning activities for digital fluency, especially for: designing playful learning activities that can provoke curiosity and understanding; designing appropriate instructional materials; and developing a range of physical-digital couplings that can be discovered, to demonstrate IoT concepts to children in a creative and intuitive way. In addition to collectively answering these three overarching questions, a number of the empirical chapters within this thesis also address more constrained sub-research questions. What these sub-research questions are, and where they occur, is detailed below in the thesis overview.

1.2 Thesis Overview

The rest of this thesis is structured as follows.

Chapters 2 and 3 review the relevant literature for considering how IoT can be taught in classrooms and how learning approaches can be evaluated, from the lenses of learning theory and previous work on teaching children about computing. Specifically, Chapter 2 first reviews notable theories from the learning sciences, including constructivism and constructionism, and defines what is meant by key constructs used throughout this thesis, including *discovery learning*, *embodied interaction* and *collaborative learning*. Next, it focuses on approaches that have been proposed so far for teaching computing to children, highlighting the gaps that exist in these approaches, especially given the changing skillset that underlies digital fluency. Chapter 3 then discusses approaches that have been adopted so far for evaluating how children learn about computing, in order to motivate the methodological approach adopted in this thesis.

Chapter 4 presents the methods adopted for the research undertaken. The methodology followed is primarily qualitative and design-focused, and is broken down into three phases: 1) developing a foundation of IoT topics, 2) iterative design and prototyping of learning activities, and 3) in the wild research to evaluate the designed learning activities in formal and informal settings.

Chapter 5 presents the work carried out for the first phase of the research, that is, developing a foundation of IoT topics. Specifically, it describes an initial interview study with IoT professionals about what IoT topics might be appropriate to teach to 8-12 year old children. The findings identify two core aspects to learning about IoT, which are *conceptual understanding* and *higher-level thinking*, together with a range of specific topics that might be considered when designing an IoT curriculum. The findings from this study are then used throughout the rest of the thesis to frame the design of introductory learning activities for teaching IoT to children.

Chapter 6 presents an overview of the technology used throughout this thesis – that is, the Magic Cubes physical computing toolkit – which was designed at UCL and provided to me as the technology to explore throughout this research. The chapter also presents the initial stages of designing discovery learning activities to teach IoT topics. It discusses the topics considered and the initial activities prototyped. It also presents an evaluation of these initial activities through a workshop with researchers knowledgeable in designing learning experiences for children, as well as reflections from public demos of the activities. The insights accrued from these initial prototyping and evaluation stages lead to design considerations for creating discovery learning activities for teaching IoT, especially in terms of how to facilitate how learners interact and reflect, and deciding on the level of instruction provided. These considerations are next used to create new introductory learning activities with the Magic Cubes, that are appropriate for children in classrooms.

Chapters 7, 8, **9** and **10** present the core empirical work carried out in classroom and public outreach settings. Collectively, these chapters address the second and third overarching research questions, that is:

- ***Can IoT topics be taught through discovery-based learning? If so, how?***

  and

- ***How can teaching IoT be made more inclusive?***

Specifically, **Chapter 7** investigates how the physical form factor of the Magic Cubes, when combined with introductory, discovery-based learning tasks in a classroom, can lead to interactions like observing and mimicking others, and sharing and taking control of the toolkit during learning. The focus of the analysis is on how these types of embodied interaction contribute to enabling 8-12 year old children to collaboratively learn about IoT concepts related to sensors and actuators, while fostering curiosity and an engaging experience. This chapter further addresses two sub-research question, that is:

> *RQ7.1: What kinds of embodied interaction strategies do children use together during collaborative discovery with the Magic Cubes and what do they learn when engaged in these? For example, do they use the physical affordances to show, point to, and share connections together?*
> *RQ7.2: Do the types of embodied interactions that they choose to employ change throughout the task?*

Chapter 8 next investigates the extent to which discovery learning can be used as a way of enabling 8-12 year old children to reflect about more complex concepts related to the IoT, beyond just understanding how IoT components work. Specifically, the focus of the study presented is on enabling critical thinking about the accuracy and reliability of sensor data. The chapter describes a classroom study where children engaged with discovery learning tasks with the Magic Cubes to measure data about their bodies and their environment. It then analyzes how this enabled them to reflect on how accurate and reliable the sensor data was, as well as the extent to which they were able to abstract away from the tasks to make generalizations about the IoT. The analysis focuses on the type and level of facilitation required to enable this type of reflection in a classroom context, providing insights into how guidance shapes learning outcomes in discovery learning with tangible interfaces. Beyond contributing to the overarching research questions, it also answers the following sub-research questions:

RQ8.1. Can discovery-based tasks enable children to think critically about sensors, sensing and sensor data in a classroom context?
RQ8.2. What are the components of critical thinking that occur during discovery-based learning?
RQ8.3. What mechanisms trigger critical thinking about IoT concepts?

One of the core goals of this thesis is to investigate how learning about IoT, and computing in general can be made more inclusive. **Chapter 9** therefore investigates whether and how the benefits of the discovery learning tasks created for Chapters 7 and 8 – especially their potential to foster comprehension, sustain engagement, and promote collaboration – carry over to a special education needs context. Specifically, this chapter presents a study carried out over a period of six weeks in a special education needs classroom with 16-19 year old teenagers. The study also provides a more longitudinal lens on learning with the Magic Cubes, by investigating how discovery learning can be followed on with coding, to enable learners to move from comprehension and reflection about an IoT topic, to more expressive learning through programming their own algorithms onto the Magic Cubes. The chapter answers the following sub-research questions:

RQ9.1: Can the Magic Cubes provide an experience that is collaborative, engaging and supports comprehension, for a spectrum of learners in a typical SEN school setting?
RQ9.2: What difficulties do learners with SEN face when interacting with the Magic Cubes? How are these overcome?
RQ 9.3: What kinds of informal methods of evaluation are appropriate for assessing the SEN students' experiences and learning?

During this PhD, beyond working in classrooms, many opportunities also arose to use the Magic Cubes in informal learning contexts, ranging from drop-in sessions at museums to structured sessions at coding events. **Chapter 10** reflects on these experiences, and considers the differences between designing learning experiences for classrooms and for more informal settings, where visitors often have different expectations and needs for the experience. The reflections answer the following sub-research questions:

> *RQ10.1. What factors need to be considered when designing learning activities for using the Magic Cubes for a diverse set of visitors in informal settings?*
> *RQ10.2. How to determine what kind of experience visitors have in these informal settings, whether they spend a short time with the Magic Cubes or a longer period of time?*
> *RQ10.3. What types of facilitation and instructional materials to provide to guide visitors when first encountering the Magic Cubes in informal settings?*

These reflections lead to practical design considerations for how learning activities can be adapted for a range of settings, in order to expand the reach of new technologies designed for teaching computing.

Finally, **Chapter 11** discusses the main findings of the research undertaken in relation to the overarching research questions posed, proposes a framework for thinking about how to teach digital fluency in the context of IoT as well as other emerging technology paradigms, and provides design considerations for discovery learning with physical and tangible interfaces. The chapter also discusses the limitations of the research and proposes future lines of work to follow on from the findings of this thesis.

Overall, the thesis demonstrates how it is possible to introduce a new approach to teaching digital fluency, enabling children of all abilities to discover future technologies and the concepts underlying how they work. It demonstrates how collaborative discovery, experimentation and reflection, supported by tangible interfaces, can work to inspire much curiosity and excitement about complex concepts related to IoT and other technologies. Through theoretical and empirical contributions, the thesis demonstrates just how much value is to be gained from coupling tangible toolkits with discovery learning in the domain of computing education. Thus, it provides directions for the design of the next generation of physical-digital toolkits for learning about IoT and beyond, that capitalize on children's playfulness and curiosity.

CHAPTER 2: LITERATURE REVIEW ON APPROACHES TO TEACHING CHILDREN ABOUT COMPUTING

Mitchel Resnick has described "digital fluency" as analogous to linguistic fluency [Resnick, 2002]. To be fluent in a language, it is not sufficient to be able to read, instead one must also be able to use the language to convey new ideas. Similarly, to be digitally fluent one must be able to not only *consume* technology, but also to use technology to *make* and *create*. Using this comparison, Resnick posited that digital fluency comprises both conceptual understanding of computational concepts, and the ability to apply these concepts creatively, for example by designing and constructing digital products [*ibid.*].

In today's digitally connected world, the skillset underlying digital fluency is considered central to the future of an engaged and innovative society. This has been recognized by numerous thinkers in policy and industry, who have argued that internationally, formal education should place increased emphasis on computing in the curriculum (e.g., [Livingstone & Hope, 2011; Quinlan, 2015]). Until recently, many computing curricula, including that of the UK, were largely focused on teaching children the skills needed to use restricted categories of software, such as word processors and spreadsheets. However, an increasing amount of new jobs have created a call for technological skills that were once required only in specialized professions [DiSessa, 2001]. Additionally, the rapid rate of technological developments means that it is not sufficient to teach children about existing technologies [National Research Council, 1999]. Instead, it is important for children to learn about the *underlying principles* of computing, as well as about transferable skills like critical thinking and complex problem solving [World Economic Forum, 2018].

Traditionally, much empirical research concerned with how to teach digital fluency skills has dealt largely with computational thinking and programming. Following on from Resnick's work, the focus of the framing of digital fluency in this thesis is broader than this, to encompass current trends and advances in computing, especially IoT. The reason for widening the remit of what students should be taught in computing classes is that traditional ICT, and even just learning to program, is no longer adequate and does not equip children with the skills they need to engage with future technological advances in society. Specifically, the approach adopted here is to extend the scope of more traditional views on digital fluency to include new concepts related to hardware components, the functionality and reliability of sensor data, as well as wirelessly connected systems. Additionally, it brings to the forefront the need to learn new ways of thinking about the societal implications and privacy of data.

This expanded notion of digital fluency raises the question: how best to teach children about the different aspects of digital fluency and to support fluid movement between conceptual understanding and higher-level critical and creative thinking? One approach is to consider how tangible and digital toolkits can be designed and used to support learning activities, covering the different aspects of digital fluency. In Section 2.1, I first consider what aspects of computing are relevant to the expanded notion of digital fluency proposed in this thesis. In Section 2.2, I discuss core themes in the learning sciences that shed light on the process of learning, in order to offer a perspective from which to analyze existing approaches for teaching computing. Finally, in Section 2.3, I discuss how existing approaches for teaching different aspects of computing have so far been designed in light of learning theory.

2.1 Four Aspects of Computing

I first consider what aspects of computing are relevant to the expanded notion of digital fluency that this thesis aims to address. I choose to focus on four ways of thinking that have been explored in research: (i) *computational thinking,* (ii) *systems thinking, (iii) thinking about hardware* and (iv) *critical thinking*. Research in the domain of teaching children about computing has investigated many other topics, including teaching about specific technology paradigms like machine learning [Hitron et al., 2019], and teaching children how to manage their privacy online [Kumar et al., 2018]. However, the four aspects are chosen here because they can be seen as directly applying to IoT. I discuss the reasoning for this in more detail and define what is meant by each of these four ways of thinking. I refer to these four chosen aspects as relating broadly to the subject of computing, and examine them mainly using computing as a lens. However, it is important to note that they also have strong links to design and technology curricula, especially in the UK [UK Department of Education, 2016]. This suggests that IoT has strong potential to fit into school subjects that extend beyond computing, per se.

(i) Computational thinking has been the subject of much debate especially with respect to learning how to program (e.g., [Lu & Fletcher, 2009; Wing, 2006]). Brennan and Resnick [2012] break it down into three core components: (i) *computational concepts,* (ii)

computational practices and (iii) *computational perspectives*. Computational concepts are the fundamental units that individuals engage with across programming contexts. These include, for example, sequences, conditionals, loops, operators and data. Computational practices are higher level "processes of construction" that individuals engage with as they work to create digital products. These include thinking incrementally and iteratively, modularizing and abstracting subcomponents of a program or product, and testing and debugging. Computational perspectives, such as questioning and expressing, relate to general ways of thinking gained through engagement with concepts and practices. It is widely acknowledged that the skillset comprising computational thinking underlies the ability to create with technology, when programming and beyond. It can also be seen to relate to IoT, especially when the goal is to teach children how to *create* IoT devices rather than just understand how they work.

(ii) Systems thinking relates to the ability to understand the interactions between parts in a complex system, as well as the emergent behaviors resulting from these interactions [Richmond & Peterson, 2001]. Basic systems thinking skills include understanding reciprocal causality – a system in which two processes influence each other simultaneously – as well as how interactions between parts can lead to non-linear causal patterns, for example through feedback loops [*ibid.*]. Though being able to engage in systems thinking has always been an important part of the professional field of computing, it has not always been considered an explicit part of the computing curriculum per se. However, I include it in this review, taking the perspective that it is essential to learning about IoT. Specifically, to understand IoT and ubiquitous

computing, it is important to understand how interactions between multiple devices can affect the behavior of the overarching system.

(iii) Thinking about hardware. Another aspect of computing that is considered here is the ability to understand the basics of hardware and physical computing components. This includes learning about microcontrollers, sensors and actuators, and the contexts in which they can be used. This is becoming a particularly crucial component of learning about computing, as the field becomes increasingly less limited to graphical user interfaces, and moves toward tangible user interfaces, ubiquitous computing and IoT. Indeed, in the UK, hardware topics like sensing, actuation and circuits are increasingly being incorporated into not just the core computing curriculum, but also the separate but complementary design and technology curriculum [UK Department of Education, 2016].

(ii) Critical thinking about technology. The fourth aspect that is included here is critical thinking about technology. Critical thinking is an important skillset in domains that extend past computing, and has been called one of the key skills for 21st century learning [Partnership for 21st Century Learning, 2019]. It is included here, because this thesis takes the perspective that learning about IoT is not just about understanding how the IoT works, or being able to design and implement an IoT device, but is also about being able to evaluate the merits and pitfalls of a technology.

Although critical thinking has been defined and operationalized in a variety of ways, key researchers in the domain, including Ennis [1985], Facione [1990] and Halpern

[1992] agree that it comprises a number of key abilities. Lai [2011] summarizes these as:

- Analyzing arguments, claims or evidence
- Making inferences using inductive or deductive reasoning
- Judging or evaluating
- Making decisions or solving problems

Being able to think critically about a specific topic has also been said to be dependent on previous knowledge (e.g., [Bailin, Case, Coombs, & Daniels, 1999]). This suggests that to be able to think critically about a technology like IoT, one must first have some conceptual background knowledge about how it works.

Despite the perceived importance of critical thinking to 21st century learning, teaching critical thinking about computing has so far been done implicitly. Specifically, while a number of environments for teaching about computing have focused on fostering problem solving when creating with technology (e.g., [Brennan & Resnick, 2012; Thieme, Morrison, Villar, Grayson, & Lindley, 2017]), the focus of this has largely been in the context of teaching computational thinking, rather than reflecting on the technology as a whole. This suggests that there is still a need to investigate how to teach critical thinking skills, when critical thinking about a technology is viewed as being able to evaluate and judge the merits and pitfalls of a type of technology, for example, in relation to privacy, security or how it fits into everyday life.

In the next section, I discuss relevant literature from the learning sciences, and summarize their implications for how they can inform the design and use of effective learning environments for teaching digital fluency. The work discussed also provides a theoretical lens through which to consider how to conceptualize the teaching of current and future computing topics.

2.2 Grounding Research in Learning Theory: Piaget, Papert, Vygotsky and Bruner

This section reviews and discusses several seminal theories in the learning sciences, which largely stem from the work of four prominent thinkers within the field: Jean Piaget, Seymour Papert, Lev Vygotsky and Jerome Bruner. The focus is on the question*: what makes for an effective learning environment?* In investigating this, the discussion deliberately remains agnostic toward a specific definition of the term *learning environment*, in order to extract several broad, theoretically-motivated principles. These principles can then be applied to a variety of learning environments, ranging from formal to informal settings and environments that make use of both digital and tangible interfaces. Moreover, this section defines a number of terms that are subsequently used throughout this thesis, specifically *discovery learning*, *embodied interaction*, and *collaborative learning*.

2.2.1 Piaget and constructivism

Piaget's constructivist epistemology serves as the foundation for much of contemporary research within the learning sciences. In positing the theory of constructivism, Piaget's writings elucidated the process of children's intellectual development. Central to constructivism is the concept of formal mental models of the world, known as *schemata*. According to Piaget, learning occurs through the iterative and progressive process of adapting schemata to make sense of personal experience [Piaget, 2013]. Specifically, Piaget argued that when *disequilibration*, or a mismatch between expectations and new information occurs, the relevant schema must either assimilate the new information, or be structurally adapted to accommodate the new information. Through this process, schemata become increasingly refined and complex, progressively allowing for more abstract and symbolic reasoning about the world [Ackermann, 2001].

Crucially, this process of adapting schemata occurs through *conscious* exploration and reflection, meaning that children must be actively involved in the learning process. It is important to note that though in applied research, the definition of constructivism is sometimes simplified to "learning by doing", using this simplification without qualifying it further may overlook Piaget's original argument that learning is a process that requires conscious reflection. Indeed, when designing learning environments, it has also been argued that reflecting is equally as important as "doing" (e.g., [Ackermann, 2001; Marshall, Price, & Rogers, 2003]). Ackermann, in particular, has been an active advocate of this idea, arguing that productive learning is a "dance" between "diving-in" through immersive exploration and "stepping-out" through reflection, and only by alternating the two can children assimilate fleeting experiences into knowledge structures [Ackermann, 2001; Ackermann, 1996].

Bruner and learning through discovery

One proposed way of supporting learning through doing and reflection is by *discovery learning* [Bruner, 1961]. Since its inception, the term discovery learning has been operationalized in a variety of ways in research. A more recent literature review describes it in a broad sense as a form of learning, where the learner is not provided with the target information, but must discover it herself by exploring the provided materials [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011]. Based on this, discovery learning is defined here as having three main tenets: (i) unstructured exploration, (ii) involving hypothesis generation and experimentation (iii) with the specific aim of uncovering an underlying model of a system or concept.

In his essay on discovery learning, Bruner argued that a discovery-based learning process can be beneficial in terms of making the target information easier to recall later on, as well as at a broader level, in terms of enabling the learner to acquire strategies for independent problem solving and inquiry [Bruner, 1961]. However, the concept of discovery learning has been subject to much debate within the learning sciences, in particular in terms of the level of instruction the learner receives. For example, Mayer [2004] cited a number of empirical examples demonstrating the failure of "*pure discovery learning*", where learners receive little, if any instruction. He discussed how the level of freedom afforded by this form of pure discovery can make it difficult for learners to select task-relevant information, which can in turn impede sense-making. Further, Mayer argued that constructivist methods like discovery learning should focus on engendering *cognitive activity* – such as selecting, organizing, and integrating information – rather than on simply supporting hands-on, behavioral activity. Here, his thesis again mirrors Ackermann's emphasis on embedding reflection in the learning process when the activity involves "learning by doing" [Ackermann, 2001].

However, it has been proposed that when discovery learning techniques are coupled with appropriate guidance, they have much promise for supporting learning [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011]. Appropriate guidance can take the form, for example, of providing the learner with worked examples before engaging in a self-guided discovery task [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011] or asking learners to explain what they are doing in a task, while providing timely feedback (e.g., [Rosenshine, 2009]). These types of guidance can then assist the learner in deciding which variables in a discovery task are relevant, thereby reducing the cognitive load of the task, while potentially enabling the learner to engage with the learning material at a deeper level than through explicit instruction [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011]. Throughout this thesis, therefore, the term *discovery learning* assumes a level of instructional guidance aimed at supporting cognitive processes related to making sense of a learning activity – for example, through guiding instructions and situated feedback provided to the learner.

2.2.2 Papert and constructionism

Another prominent thinker in the learning sciences was Papert, who built on the work of Piaget through his theory of *constructionism.* Constructionism adheres to many constructivist principles, and agrees with the essential Piagetian view that learning is an active process, and that knowledge is progressively constructed through personal experience [Papert, 1980]. However, constructionism additionally offers insight into the roles of *context* and *tools* in effective learning [Ackermann, 2001]. In particular, it explicates how learners contextualize and connect new knowledge with prior knowledge. It posits that a powerful means toward this end is *externalizing ideas* through the construction of public entities, or in Papert's terminology, *objects-to-think-with.* Papert posits that objects-to-think-with are both a means of situating new information within the social context, and a tool for expressing, communicating and clarifying ideas [Papert, 1980].

The role of embodied interaction

An additional potential benefit of *objects-to-think-with*, especially those that are instantiated through physical rather than digital means, is that they can engender embodied interaction. Within HCI, there has been an assortment of definitions for the idea of 'embodiment'. This is in part due to the fact that the term is conceptualized differently between a number of fields from which HCI research heavily draws, including cognitive science, cognitive linguistics and artificial intelligence [Melcer & Isbister, 2016]. In defining embodied interaction, this thesis looks to the work of Dourish [2004]. Drawing on the field of phenomenology, Dourish [2004] defines embodiment as the property of being part of the physical and social world. By this definition, embodiment is not just a physical property (i.e., the property of having a body) but is crucially tied to *participation* in the world – for example, through physically interacting with the environment and socially interacting with others. Through this lens, embodied interaction can be defined as "*the creation, manipulation, and sharing of meaning through engaged interaction with artifacts*" [*ibid.*].

What, then, is the educational value of embodied interaction? By taking the central perspective that the way in which we construct and share meaning is intrinsically tied to 'being' embodied, it follows that designing learning environments that capitalize on embodied interaction – for example those which involve tangible and social elements – might be conducive to supporting understanding and sense-making. For instance, these types of environments can support the offloading of cognition into the real world, and linking abstract ideas to external representations [Antle, 2013]. More generally, they can leverage students' preexisting knowledge of the physical and social worlds to facilitate understanding when learning with artifacts (physical or conceptual) such as physical cubes and games (e.g., [Dourish, 2004; Jacob et al., 2008]).

Here, I use the concept of embodied interaction more specifically to refer to the observable gestures, physical movements and dialogue that learners employ when interacting in a situated context. Observing these aspects of interaction can help understand how learners discover the functionality of a tangible/physical artifact, as well as helping explain how they can lead to the assimilation of higher level abstractions. Using this framing of embodied interaction can also provide an account of how the properties of a physical artifact can lend themselves to coordination of action and the sharing of understanding between people [Hornecker & Buur, 2006]. This theoretical framing of embodied interaction is considered highly relevant to learning about IoT and digital fluency and is also used in the thesis to account for how children learn about abstract concepts when using a tangible toolkit together with their peers.

Next, I return to Papert's constructionism in order to introduce Vygotsky's social constructivism and to discuss in more detail how social interaction, in particular, can contribute to learning.

2.2.3 From Papert to Vygotsky: contextualizing and clarifying knowledge

In emphasizing contextualizing knowledge within a social context through the construction of public entities, Papert's work is evocative of that of Vygotsky, the pioneer of *social constructivism*. Vygotsky, who saw language as a crucial tool for effective learning, argued that dialogue leads to collaborative co-construction of knowledge between individuals [Vygotsky, 1978]. Although Vygotsky's dialogic perspective and Papert's objects-to-think-with are epistemologically distinct, underlying them is a common thread. Both dialogue and objects-to-think-with can be viewed as a means for clarifying and communicating mental representations of knowledge, and both are tools that can embed abstract and complex ideas into a situated context.

On collaborative learning

Another common thread between Vygotsky and Papert is their emphasis on collaboration between individuals as a means of scaffolding learning. For example, Vygotsky, through his construct of a Zone of Proximal Development, proposes that a child's problem solving abilities can be substantially enhanced "under adult guidance, or in collaboration with more capable peers" [Vygotsky, 1978]. Papert, in turn, emphasizes the importance of "learning cultures", envisioning informal learning environments where members work collaboratively to build a common understanding [Papert, 1980].

Beyond Vygotsky and Papert, there has been much empirical interest in collaborative learning. However, this raises the question: what is actually meant by collaborative learning? Roschelle and Teasley [1995] define it as a process where individuals "negotiate and share meanings" in order to collaboratively construct new knowledge. This contrasts with cooperative learning, where learners split up a learning activity into subtasks to carry out independently, which they then bring together into a common output [Dillenbourg, 1999; Stahl, Koschmann, & Suthers, 2006].

A key reason that collaboration is considered to be effective for learning is because it can engender types of behavioral activity that may not arise when an individual is learning alone – for example, explaining, disagreeing and discussing. According to Dillenbourg [1999], activities like explaining, disagreeing and discussing can then trigger cognitive mechanisms that are important to learning, like knowledge elicitation and internalization. Although these cognitive mechanisms are not necessarily contingent on collaboration, the field of research concerned with collaborative learning shows how designing collaborative learning environments can support them. Therefore, collaborative learning is not viewed as a learning mechanism in itself – rather it is defined as a situation, where cognitive mechanisms that contribute positively to learning can be anticipated to arise [*ibid.*]. Accordingly, in this thesis, collaborative learning is not treated as a method in itself, but viewed as a type of learning environment through which to promote discussion and reflection among children.

Learning cultures and the importance of student-directed learning

Finally, I return to Papert's vision of "learning cultures," which underlines the importance of student-directed learning. In student-directed learning, individuals select learning activities that match their interests (e.g. [Kafai, 2002]). This idea has its roots in critical pedagogy, which pushes back against decontextualized learning, arguing that learning environments should seek to meaningfully connect the knowledge that is to be learned with a child's prior experiences and interests (e.g., [Dewey, 1902]). It is based on the premise that learning environments that provide a curriculum that is meaningful to the individual, rather than one that is abstract and decontextualized, can support not just knowledge integration, but also more sustained engagement with what is to be learned [Dewey, 1902; Freire, 1973].

2.2.4 Summary

In sum, the theories and conceptual framings discussed as part of the literature review were chosen for their potential, firstly, to account for factors that contribute to successful learning and, secondly, to inform the design of learning environments for teaching digital fluency. Specifically, while Piaget's work outlines the blueprints for cognitive integration and retention of knowledge, the works of Papert and Vygotsky highlight the influence of objects, language, and social context in learning.

From the theories described, it is evident that learning is a multifaceted phenomenon, which is closely tied to a variety of factors, including *collaboration*, *cognitive activity* and the *context in which concepts are taught*. These factors are considered of primary importance in this thesis especially when determining how to design and evaluate appropriate learning environments. They show that an important consideration when designing learning activities for teaching IoT concepts is to think how to enable the learning to be personally meaningful, social, and to provide opportunities to externalize what is being learned. They also suggest that it is key that learning activities support learners in reflecting on what is being taught, rather than just engaging them in behavioral activity. Thus, a primary goal in this thesis is to investigate how to design introductory discovery learning tasks with appropriate guidance, in a way that enables children to reflect on abstract concepts related to computing and IoT. Another core goal is to investigate how the benefits of embodied interaction with physical artifacts – for example, their potential to help with cognitive offloading and with linking abstract concepts to external representations – can be combined with a collaborative setting, in order to help children build understanding of new concepts together.

In terms of evaluation, the concepts of embodied interaction and collaborative learning, as discussed in this section, are also viewed in this thesis as a lens through which to analyze the efficacy of a learning task. Specifically, where embodied interaction and collaborative dialogue are often readily observable as learners complete a task, there seems to be much potential to use them as an analytic lens through which to glean how effectively the learning process unfolds, given a particular learning environment.

Next, I discuss how other researchers have used a particular conceptual approach when designing new technologies and approaches to teach children about computing topics. As the next section will demonstrate, many approaches to date have employed ideas from constructionism, especially Papert's concept of *objects-to-think-with*, with some also basing their design on enabling student-directed learning, especially in bodies of work on programming and maker spaces. Moreover, a number of approaches, especially from the body of work on tangible interfaces for learning, have viewed facilitating embodied interaction and collaborative learning as being of central importance. The next subsections focus on how these conceptual approaches have been used for: (i) *learning about computing through programming;* (ii) *embodied and collaborative learning with tangible user interfaces;* (iii) *physical computing, the maker movement and expressive learning;* (iv) *teaching children about IoT; and* (v) *making computing inclusive.*

2.3 Approaches to Teaching Children about Computing

2.3.1 Learning about computing through programming

Teaching computing to children is often done through programming, particularly in formal learning environments. Much research has been conducted to determine what are the most effective approaches to introducing programming – since it is well known that learning to program is difficult.

Early research on programming for children

Papert developed the Logo programming language based on his theoretical ideas of constructionism [Papert, 1980]. Logo was designed to enable children to explore formal mathematics in a more concrete and engaging way, based on the idea of 'objects-to-think-with'. Instead of asking children to program mathematical equations in abstract syntax, Logo enables children to program the movements of a physical turtle using simple commands, such as "PEN DOWN FORWARD 10". This approach has been shown to have several advantages. The simple structure of the Logo syntax removes much of the complexity of programming, allowing children to concentrate on the concrete goals of moving the turtle agent. Furthermore, Papert argued that Logo enables "body-syntonic reasoning", allowing children to reason about the actions of the turtle by relating them to knowledge of their own bodies [*ibid.*]. This, in turn, serves as a powerful tool for reflecting on what they are learning and also "debugging" of their reasoning about the program they are coding.

Logo was used widely in the late 1970s and 1980s as personal computers became more readily available, and as a result of teaching initiatives like the Computers in Schools

Project, soon became a tool used by numerous schools [Logo Foundation, n.d.]. In addition, the publication of Papert's influential book, *Mindstorms* [Papert, 1980], which detailed the motivations for teaching computational thinking in primary and secondary curricula, further sparked much interest in how to use computers in innovative ways to support learning.

Teaching systems thinking through programming

These successes of Logo then led to developments in using programming as a means of conveying "powerful ideas" in domains other than mathematics. Notable examples include StarLogo and NetLogo, both of which were designed to convey concepts relating to complex systems [Resnick, 1997; Tisue & Wilensky, 2004; Wilensky & Resnick, 1999]. In both StarLogo and NetLogo, users can program the behavior of several agents and subsequently observe what emergent, sometimes surprising, effects can arise from their interactions [Tisue & Wilensky, 2004]. Though emergence and complex systems concepts have been shown to be difficult for children to grasp (e.g., [Jacobson & Wilensky, 2006]), it has been suggested that these post Logo approaches allow children to relate the individual behavior of the agents to their own bodies, which may aid their understanding of the complex system as a whole [Horn, Brady, Hjorth, Wagh, & Wilensky, 2014]. In addition, in StarLogo and NetLogo, the agents can be modeled after a variety of objects in the real world, enabling explorations of various complex systems. For example, specifying the behavior of several cars can lead children to gain insight into the nature of traffic jams [Wilensky & Resnick, 1999], and modeling frog populations over time has been found to support understanding of the systems underlying evolution and natural selection [Horn, Brady, Hjorth, Wagh, & Wilensky, 2014].

Interest-driven and creative programming

More recent research in children's programming languages has strived not only to enable them to understand formal computational concepts, but also to reimagine programming as a tool for interest-driven creativity and innovation [Resnick, 2006]. The most notable example is Scratch, a visual block-based programming language, developed by the MIT Media Lab [Resnick et al., 2009]. In Scratch, children program graphic agents called "sprites" by dragging together visual, puzzle-like blocks. Sprites can be, for example, images of animals or people. The visual blocks, similar to Logo's simple syntax, make traditional programming constructs like variables and data structures less abstract, and prevent children from making syntax errors that can detract from focusing on the computing constructs that the code represents [*ibid.*]. These features have been found to significantly lower the entry threshold to programming, making it more accessible and inclusive to a diversity of children with different abilities.

Scratch also adheres to Papert's constructionism. Scratch sprites serve as public entities that children can use to externalize their understanding of coding constructs, and their behavior – like the behavior of the Logo turtle – has been suggested to encourage body-syntonic reasoning. Furthermore, Scratch projects have also been posited to be a powerful tool for children to "debug" their understanding of computational principles [Resnick, 2012]. Another important aspect of Scratch is the online community that has been built up around its use, to which users can upload, collaborate on, and discuss projects. This sharing mechanism provides a meaningful social context to programming. Scratch is still largely used for coding digital, self-contained programs, although, recently, developers have extended its capabilities to enable children to also engage with physical computing and cloud data. For example, it is now possible to connect Scratch to several physical platforms, including the Makey Makey [Lee, Kafai, Vasudevan, & Davis, 2014], LEGO WeDo and the micro:bit ["Scratch - micro:bit," n.d.; "Scratch - WeDo 2.0," n.d.]. Scratch researchers have also extended the software to enable children to use persistent, cloud-based data in their projects [Dasgupta, 2013; Dasgupta & Hill, 2017; Dasgupta & Resnick, 2014]. These additions make Scratch a more flexible tool for learning about computing, by extending the variety of concepts encompassed by the software to include those related to hardware and data. However, at the time of writing there has been little published evaluation of how these extensions have changed how children learn to program or understand computing concepts.

The online community has also provided Scratch researchers with a very large dataset of uploaded programs with which to analyze the progression of children's computational thinking development [Brennan & Resnick, 2012]. Analyses of this dataset have shown increased complexity and breadth in the projects of users who remain active in the Scratch community over a longer period of time, suggesting that Scratch may be a powerful tool for longitudinal skill development [Matias, Dasgupta, & Hill, 2016].

In sum, the body of research investigating how to lower the entry threshold to learning programming and computational thinking has demonstrated the efficacy of key tenets of learning as posited by Papert's constructionism [1980]. Specifically, they have supported the constructionist ideas that learning should be an active, hands-on process, and that objects-to-think-with – digital or physical – can promote easy and effective exploration of abstract concepts, such as those related to mathematics, systems thinking and programming. In addition, Papert's [1980] physical Logo turtle indicated that adding physicality and embodied interaction to the learning process can help learners leverage preexisting knowledge about the world, in order to scaffold learning of abstract concepts.

We have seen how constructionism has played an instrumental role in shaping digital learning platforms, both with and without physical artifacts. There has also been a body of research that has explored what types of learning computationally-augmented tangible artifacts themselves, can afford. This is presented in the next section.

2.3.2 Embodied and collaborative learning with tangible user interfaces

Ishii and Ullmer's vision of "tangible bits" [Ishii & Ullmer, 1997], where they conceptualized the benefits of developing interfaces that merge the physical and digital has inspired a whole body of research on tangible user interfaces (TUIs). In particular, a wide variety of TUIs have been developed to support education. It has been suggested that TUIs can be particularly beneficial in supporting young learners because they are related to physical experiences in the real world (e.g., [Zaman, Abeele, Markopoulos, & Marshall, 2011]), and as such, can make complex concepts easier to relate to previous knowledge. Another main postulated benefit of tangible interfaces is their potential to foster collaborative behavior [Antle & Wise, 2013], making them particularly valuable within the learning domain. In particular it has been suggested that the physicality of TUIs can make it easier for children to interact with them together [*ibid.*]. It has also been suggested that they can support children in formulating a joint problem space, through which they can collaboratively generate and refine hypotheses [Suzuki & Kato, 1995]. Dourish's [2004] theoretical ideas about the embodied properties of tangible interfaces have also inspired a number of researchers to investigate the ways in which embodied interaction might influence the learning process in studies using tangibles (e.g., [Klemmer, Hartmann, and Takayama 2006; Melcer, Hollis, and Isbister 2017; Thieme et al. 2017]) .

TUIs for programming

One of the first attempts at creating a physical interface for teaching programming skills was AlgoBlock [Suzuki and Kato 1995], a tangible programming interface aimed at promoting shared learning of computational thinking concepts. The evaluation of AlgoBlock showed how its affordances for physical gestures enabled mutual monitoring of action, in turn promoting joint understanding between children [*ibid.*]. As an early prototype, the AlgoBlock interface only allowed limited exploration of programming concepts. However, more recent works have built on the ideas proposed in AlgoBlock, leading to the creation of more flexible and extensible tangible programming languages. Tern, for example, is a kit comprising wooden puzzle pieces which can be connected together to create basic programs that include parameters, loops and subroutines [Horn and Jacob 2007]. The physical configuration of Tern's wooden blocks, once scanned using a portable scanner, controls the movements of a virtual robot. Similarly, Robo-Blocks consists of physical command blocks that control a physical robot, and has been shown to help primary school aged children with learning to debug programs [Sipitakiat and Nusen 2012].

More recently, companies like Google and Microsoft have developed tangible programming kits consisting of connectable blocks. Microsoft's Code Jumper (previously called Torino), for example, is designed to be usable by all children including blind and visually impaired children [Morrison et al. 2018]. Specifically, the Code Jumper blocks use music as the output, and are designed to enable users to differentiate them through touch. Google's Project Bloks has been designed as a general platform through which new tangible programming interfaces can be created [Blikstein 2019; Blikstein et al. 2016]. The goal of Project Bloks is to enable educators and designers to experiment with new form factors for tangible programming interfaces, without having to implement the low-level technical details of the system. These new platforms demonstrate that there is much drive in industry for commercializing tangible programming interfaces. This is in part because this category of interfaces has shown much promise for enabling novices to easily get started with learning about programming – including children as young as five and other groups that digital programming can sometimes exclude [Blikstein et al. 2016; Morrison et al. 2018].

Others have deviated from the "connected blocks" approach for tangible programming by exploring different form factors. Curlybot, for example, was designed as a purely physical correspondent to Logo's turtle [Frei et al. 2000]. Embedded with kinetic memory, Curlybot allows children to program its geometrical movements by "instructing" it through direct physical manipulation, then replaying the motions. An interface that extended the functionality of Curlybot, was Topobo, a reconfigurable robot toolkit that can similarly be programmed to replay actions using its kinetic memory [Raffle, Parkes, and Ishii 2004]. Topobo and Curlybot can be used as tools with which to explore "powerful ideas" in maths and science, for example DNA structures and parabolas [Parkes, Raffle, and Ishii 2008]. However, as the programming in these interfaces is implicit, a question is whether they encourage enough reflection about the process and conceptual basis of programming to enable learning of the underlying computational thinking concepts. The evaluations of Curlybot and Topobo have not examined this question in detail.

In terms of learners' performance on learning outcomes alone, it has been found that TUIs (outside the domain of teaching programming) do not categorically outperform graphical interfaces [Marshall, Cheng, and Luckin 2010; Zuckerman and Gal-Oz 2013]. However, the counterargument is that compared to graphical interfaces, TUIs have the added benefit of being able to support collaborative learning and reflection through dialogue more extensively and easily (e.g., [Horn, Crouser, & Bers, 2012; Suzuki & Kato, 1995]). They do this because as compared to a computer screen, for example, all can see them and they can be easily shared while supporting joint attention. In addition, it has been suggested that students often prefer to engage with TUIs compared with analogous graphical interfaces when learning computational concepts [Melcer & Isbister, 2018; Zuckerman & Gal-Oz, 2013]; this has been attributed to the high level of realism and physical interaction that they afford, leading to a more engaging experience [Zuckerman & Gal-Oz, 2013].

However, a question that remains is how the learning outcomes related to *learning programming*, resulting from the use of a tangible programming interface compare to those from the use of a graphical programming interface. Although short-term comparative studies have shown that children are able to grasp core computational concepts like sequences and repeats through TUIs for programming just as well as through comparable graphical user interfaces (e.g., [Horn et al., 2012; Strawhacker & Bers, 2015]), there is still a lack of in-depth research about how longitudinal learning outcomes differ between tangible programming and programming through a graphical interface. In particular, where tangible programming interfaces are often more limited in terms of the code complexity they support, a question this raises is to what extent they can support learning about programming over time, beyond basic concepts. Based on the evidence of their other benefits (e.g., in terms of collaboration and engagement) they can perhaps be seen most effectively as 'bridging' tools, whereby they initially support novices in learning basic computing constructs, before they move on to learning with more complex programming environments.

TUIs for discovery learning

The properties of TUIs are also assumed to support learning through exploration [Marshall, 2007]. By exploratory learning is meant where the learner interacts with an existing model or system, as opposed to constructing or programming a new model or system. Learning through exploration is also supported by constructivist schools of thought [Piaget, 2013] and has been suggested to be particularly suited as an introduction to new concepts [Marshall, 2007; Schneider, Bumbacher, & Blikstein, 2015]. As described in Section 2.2, one kind of learning through exploration is *discovery learning*, which involves the learner engaging in independent, unstructured exploration to uncover target information that is not provided to them directly.

Discovery learning with TUIs has been suggested to be an effective approach for promoting retention of learning outcomes, more so than direct instruction with the same interface [Schneider et al., 2015]. The reason for this might be that discovery-based tasks with tangible interfaces give rise to self-guided, embodied interaction. In turn, this can trigger cognitive processes, like sense-making and knowledge integration. For example, it has been argued that embodied exploration facilitated by discovery-based, tangible artifacts can engender cognitive activity, even when the exploration is not directly focused on the target learning concepts [Price & Falcão, 2011]. An example in Price and Falcão's study [2011], where a discovery task was set up with a TUI to engage children in learning about the physics of light, was where children spent much time engaging in activities that were tangential to the learning task, like exploring how to generate different patterns of light – in addition to just the time spent explicitly figuring out how light absorption and reflection work. Their analysis found that this type of tangential activity provided children with concrete instances that helped them build their understanding of the rules of the system, even though they were not explicitly reflecting on the physics of light at the time.

Within the broader body of work on interfaces for learning, a number of digital-physical interfaces have been designed to facilitate discovery learning for a given topic/domain, including using combinations of physical and digital representations for tasks related to color mixing [Rogers, Scaife, Gabrielli, Smith, & Harris, 2002], the physics of light [Price & Falcão, 2011], and physiological systems [Schneider et al., 2015]. Evaluations of these interfaces have shown them to support domain-related understanding, playfulness and high levels of sustained engagement during interaction.

Within the domain of teaching about computing, more specifically, several TUIs have been designed to capitalize on learning through discovery, rather than on learning through programming. One strand of work in this domain has dealt with teaching systems thinking concepts, such as feedback loops and emergence [Resnick, 1998]. Because systems thinking is traditionally taught in formal, largely theoretical contexts, - often making it inaccessible to younger audiences - it has been suggested that discovery-based TUIs can lower the entry threshold to exploring these topics [Zuckerman, Arida, & Resnick, 2005]. Resnick et al. [1998] developed several TUI prototypes to explore how discovery-based learning could be capitalized on when learning about computing. A core design principle used was to create socially meaningful objects by tapping into the interests of children. For example, based on the idea of cellular automata, the authors designed jewelry beads augmented with microcontrollers and LED lights [*ibid.*]. The beads were pre-programmed with various behavioral rules, such as "pass light on to the next bead", and placing beads next to each other created emergent, dynamic light effects. Additionally, more advanced learners were able to program the beads with their own rules, and then observe the emergent behaviors. However, the prototypes were not empirically evaluated with respect to how they supported the learning process, and as such little is known about their efficacy in supporting the intended learning outcomes.

Another development was System Blocks, a toolkit designed to reflect core systems thinking principles, such as stocks (quantities of matter at a specific interval in time) and flows (rates of flow of matter between stocks) [Zuckerman et al., 2005]. System Blocks enables children to reflect on real-world systems by visually observing quantity changes between the tangible blocks representing stocks and flows. For example, a simulation could involve observing the relationship between the quantity of water in a bathtub and the inflow and outflow of the water. A particular merit of the System

Blocks interface is its explicit tie to real world contexts: to activate the simulation, children use tagged picture cards that relate to everyday situations, such as baking cookies or going to a sports game. System Blocks has been shown to encourage discussion and "debugging" of mental representations through dialogue, as well as to promote knowledge transfer of implicit systems principles from one system (e.g., flow of water) to others (e.g., baking cookies) [*ibid.*].

This type of approach of employing discovery-based systems to enable knowledge transfer has more recently also been demonstrated to be suitable for teaching children (10-13 years old) about machine learning principles [Hitron et al., 2019]. In this study, children were asked to train a machine learning system with different types of hand gestures and label the hand gestures into categories; throughout the process, they were able to observe how the system classified hand gestures based on how they had trained it. In this way they were able to figure out the mechanics of machine learning, for example, that to train the system to recognize a circle, the system had to be trained on circles of many different sizes. In a post-interview, this process was found to enable the children to relate the importance of creating a large and diverse dataset to other machine learning systems. There is much evidence these types of discovery-based interfaces can help children with understanding specific systems, and carrying over their knowledge to other systems. However, due to their highly situated nature, a question this raises is whether they are conducive to the generalization and understanding of the *underlying principles* of systems thinking or machine learning. What also remains is the question of how much and what type of feedback is needed in these types of discovery learning activities, to enable children to extrapolate and reflect on concepts that are embedded in the task, for example, systems thinking principles like stocks and flows, or machine learning principles like data labeling and evaluation.

Next, I consider how physical computing and making activities can help children learn about computing.

2.3.3 Physical computing, the maker movement and expressive learning

In recent years, there has been the emergence of what has been termed the "maker movement". The maker movement, which aims to support wider audiences in engaging with creative digital fabrication and coding (e.g., [Arduino, n.d.; Gershenfeld, 2008]), is concerned with countering the trend in formal education toward instructionism, and instead embracing constructivist and constructionist approaches to learning [Blikstein, 2013]. Here, two core enabling aspects of the maker movement are explored, *toolkits for making* and *community spaces for making.*

Toolkits for making

The roots of today's varied toolkits for making can be traced back to the LEGO/Logo toolkit at the MIT Media Lab [Resnick & Ocko, 1990]. This toolkit consisted of computationally augmented LEGO blocks, including sensor and actuator parts, which could be reprogrammed through an extended version of the Logo language. With developments in smaller and cheaper hardware components, the group went on to design progressively smaller and more flexible prototypes, including LEGO Mindstorms [Martin, Mikhak, Resnick, Silverman, & Berg, 2000] and the Cricket [Resnick, 1998].

During this time, other research groups were simultaneously creating "toolkits for making" for a different audience, that is, for the emerging "hacker" community. One of the most notable developments was Stanford's BASIC Stamp, which was quite distinct from the child-oriented developments happening at the MIT Media Lab. Rather than concealing hardware components, like pins and sensors, it left them exposed, with the aim of demystifying the often obscured world of electronics [Blikstein, 2015]. Many developers of child-oriented toolkits for making subsequently adopted this design approach, which was later recognized to be pertinent for teaching about what embedded systems are and how they work.

Today, a wide variety of physical computing toolkits for making have been developed. These have become particularly popular within "maker communities", which are encouraging diverse audiences to learn about computing through creative coding and fabrication. Such toolkits – like Arduino, LittleBits and RaspberryPi [Arduino, n.d.; Bdeir, 2009; Raspberry Pi, n.d.] can help with learning about not only computational thinking, but also about *understanding hardware* and potentially *critical thinking about technology*. The making toolkits can largely be classified into two categories. These are *low floor, low ceiling*, and *high floor, high ceiling* [Resnick et al., 2009]. On the *low floor, low ceiling* end of the spectrum lie toolkits like Makey Makey, which allows users to create their own user interfaces by connecting everyday conductive objects (e.g. fruit, pencil graphite) to a circuit board with alligator clips [Beginner's Mind Collective & Shaw, 2012]. Other toolkits teach about circuits, hardware and sensors through magnetic, connectable components (e.g., LittleBits) or through step-by-step construction of a pre-defined design, such as the MakeMe cube [Johnson, Shum, Rogers, & Marquardt, 2016]. Both Makey Makey and LittleBits can be considered low floor because they are, by design, easy to get started with and do not require any preexisting knowledge about hardware. Both are considered low ceiling in the sense that they support limited computing skills progression. In contrast, the *high floor, high ceiling* toolkits allow for more complex skills progression to take place, however are also considered high floor because they are substantially more difficult to get started with. They typically consist of microcontrollers, sensors and a designated programming language. Some, like the Arduino, are also supported by online communities, which encourage collaborative problem solving. Other more advanced toolkits comprise computer-on-a-chip platforms, such as the RaspberryPi, Microsoft's .NET Gadgeteer [Villar, Scott, Hodges, Hammil, & Miller, 2012] and the WiFi enabled Kniwwelino [Maquil, Moll, Schwartz, & Hermen, 2018].

Despite the popularity of *high floor, high ceiling* toolkits, most notably Arduino, in schools and maker spaces, it has been argued that their physical design is not the most suitable for learning the basics of programming at a beginner's level [Blikstein, 2015]. This is particularly because to carry out relatively simple tasks, like creating a program to blink an LED light when a sensor level exceeds a threshold, children may have to dedicate a disproportionate amount of time to carrying out complex tasks, like setting up connections on a bread board, which are ultimately not related to the target learning outcome at hand [*ibid.*]. This has led to calls for further research investigating how to design toolkits that can be considered *low floor* and *high ceiling*. These can be envisioned as flexible toolkits for making and learning about computational thinking that enable appropriate scaffolding at each point in the learning trajectory, and support both computing novices and more experienced learners [*ibid.*].

An emerging area of research has been to design toolkits that offer both a low entry threshold, and high flexibility of use. One attempt to achieve this has been the UCL Engduino [Baker et al., 2014; Engduino, n.d.], an Arduino-based board that comes with a variety of embedded sensors and output devices, which allows children to immediately explore hardware functionality without requiring time-consuming setup. Another example is the BBC's micro:bit [Micro:bit, n.d.], designed to enable children to make, create and code in classroom settings. The micro:bit was designed to be inexpensive, accessible, and engaging in order to combat the decrease in interest in studying computing in the UK [Rogers et al., 2017]. Like the Engduino, it has a variety of embedded sensors and a small LED matrix that is intended to make learning about the hardware easy to get started with. In addition, it can also be used with a variety of extensions to enable more advanced making and coding[1]. The toolkit has four integrated programming environments that can be used online, ranging from easy to more complex, as well as an emerging online community that offers tutorials for both beginners and more advanced learners. To date, the micro:bit is experiencing widespread use in primary and secondary schools in the UK, as well as increasing use in other countries including Iceland, Finland and Singapore [Micro:bit, n.d.]. Studies of its use in schools are still emerging, but so far have shown that both children and teachers perceive it to be an engaging way of learning about physical computing, and as a tool that enables creativity [Sentance, Waite, Hodges, MacLeod, & Yeomans, 2017; Sentance, Waite, Yeomans, & MacLeod, 2017]. However, what research so far has also revealed is that work still needs to be done in terms of creating resources and support

[1] https://makecode.microbit.org/extensions

structures that enable *teachers* to learn more about the different use cases of the micro:bit, as well as help them develop activities that build on each over a longer period of time [Sentance, Waite, Yeomans, et al., 2017].

The UCL Interaction Centre's Magic Cubes [Marquardt, Lechelt, Rogers, & Shum, n.d.] were also developed with the goal of being *low floor* and *high ceiling*. Specifically, the Magic Cubes aim to lower the entry threshold for exploring fundamental hardware and computing concepts, through a highly flexible toolkit. They comprise interactive sensing cubes, designed as part of a non-intimidating, all-in-one toolkit for exploring sensors and programming. In addition, the cubes are embedded with Bluetooth modules, through which they can connect to other cubes. The intention of this was to provide a way of making the platform extensible so that they could be used for teaching about systems thinking and IoT. Due to their flexibility and range of IoT-relevant features, the Magic Cubes were chosen as the technology to explore how to teach digital fluency in this thesis; Chapter 6 provides an in-depth overview of their design and features.

Community spaces for making

The maker movement has led to the rapid development of "maker spaces" worldwide: physical spaces set aside for communities to engage in digital and physical fabrication. Maker spaces are developing in local communities (e.g., [Rusk, Resnick, & Cooke, 2009]), as well as in schools in support of the STEM curriculum (e.g., [Blikstein, 2013]). The core idea of maker spaces is to encourage member-directed learning, where members learn by exploring new technologies and engaging with physical computing and fabrication. This approach has several benefits. Particularly, the emphasis on interest-driven creation within maker spaces allows for meaningful bridging of the traditional gap between academic and day-to-day life [Blikstein, 2013], which has been suggested to support learning [Dewey, 1902; Freire, 1973; Papert, 1980]. Moreover, in maker spaces, members are encouraged to iterate through the whole process of creation, from conceptualization to fabrication [Mikhak et al., 2002]. This approach has the advantage of democratizing important aspects of computing that are not traditionally taught in schools, or in fact through many other approaches discussed in this review, such as thinking critically about how a technology fits into a particular context. However, makerspaces have a number of limitations as a method for teaching computing to children, when the goal is to convey specific learning outcomes. For example, maker activities (by design) are usually not tied to deliberate learning goals [Cohen, Jones, Smith, & Calandra, 2017]. Moreover, as makerspaces are by design informal learning environments where learners choose when to engage with instructors or guidance (e.g., [Bar-El, Zuckerman, & Shlomi, 2016]) it can be difficult to control for what abstract computing concepts a learner comes across during the making process, and the extent to which they reflect on these – as compared to more controlled learning environments.

With the rise of recent frameworks that outline how learning practices, that are core to makerspaces, can be encouraged by instructors – for example inquiry, iteration and knowledge sharing – there seems to be much to learn and carry over, from the maker space approach to other informal and formal learning environments (e.g., [Cohen et al., 2017; Wardrip & Brahms, 2015]). For example, new technologies and learning resources for teaching about computing in the classroom might be designed with encouraging peer feedback on work, and fostering students' autonomy over their learning, in mind.

2.3.4 Teaching children about IoT

With the growing importance of IoT and ubiquitous computing to society's everyday interactions with technology, an emerging empirical question is how the benefits of the approaches discussed in the previous sections, can be best combined and extended to teach IoT topics to children.

In recent years, there has been an emerging body of research concerned with teaching IoT at the post-secondary level. Specifically, a number of university-level IoT courses have been designed [Ali, 2015; Kortuem, Bandara, Smith, Richards, & Petre, 2012; Szydlo, Brzoza-Woch, & Konieczny, 2018], which have begun to shed light on what IoT topics might be appropriate to incorporate into computing curricula for adults. The content of these courses provides students with an understanding of the computational concepts and infrastructure underpinning IoT, largely through learning through practical methods like tinkering, programming and making with IoT hardware. The motivation behind this approach is to convey key IoT topics related to embedded programming, networking protocols, and distributed computing [Ali, 2015]. In addition, some have also endeavored to encourage students to engage with creative and critical reasoning about the design of IoT systems [Kortuem et al., 2012].

In a recent review of existing courses and toolkits for post-secondary IoT education, Burd et al. [2018] propose that they should cover three main areas: (i) hardware; (ii) connectivity, the cloud and data; and (iii) human-computer interaction. Specifically, in terms of *hardware*, they suggest teaching about how embedded hardware – like sensors and actuators – can interface with the environment, by collecting, processing and outputting data (e.g., through lights or motors). In terms of *connectivity, the cloud and data*, they propose that course curricula should convey how data is transferred between devices, where it is analyzed, as well as the implications of this type of connectivity on the security of the system. Thirdly, they suggest that *human-computer interaction* should also be a key focus of IoT courses, in order to engage students with the importance of designing IoT systems that factor in how well people understand them and how easy they are to use by others. Together, these three topics cover the conceptual architecture of IoT and provide students with the tools to start building IoT devices; moreover, by teaching about the human-computer interaction and security side of IoT, they can also engage students in thinking critically about the implications of an IoT system. All of these aspects of learning are important to the idea of digital fluency.

The research reported in this thesis focuses primarily on children aged 8-12, as well as Special Education Needs (SEN) students aged 16-19. The curriculum proposed by Burd et al. [2018] might seem a feasible place to start to think of what to teach them. However, the extent to which these topics can, or should be, be appropriated for younger schoolchildren is unclear. This is because not all of the proposed topics may be relevant to children just starting to learn about computing. For instance, while teaching children about how data is sensed and actuated through physical hardware may be a good building block for teaching how IoT works, it needs to be considered whether there is value in teaching children how to use different networking protocols, or what specific security algorithms are. Beyond this question of how relevant the topics are to children, is the question of how easy it would be for children to understand these topics. Many of them would likely require considerable abstraction that may too difficult for this age group to comprehend. The question this raises is can they learn all three aspects or is it expecting too much of them? Should a more streamlined approach be adopted that scaffolds the topics taught more? If so, which topics to teach and how?

In order to address what level is appropriate, the aims of the research reported in the thesis were to investigate (i) which IoT topics are appropriate for children aged 8-12 and (ii) how these might be taught, especially by building on existing successful approaches to teaching computing already mentioned. A further aim of this thesis was to investigate (iii) how to make this new kind of computing teaching inclusive to all children – focusing in particular on Special Education Needs students aged 16-19 – which is seen as an important goal of the research and which I now discuss in more detail.

2.3.5 Making computing inclusive

Most of the approaches to teaching about computing described above have been concerned with teaching computing to children *in general*. However, designing for a general audience does not always mean that the technology will be suitable for all. One of the foci of this thesis is to be inclusive when designing approaches for teaching children about IoT – given that computing is central to everyone's lives. Sharp, Rogers and Preece define inclusive design as "an overarching approach where designers strive to make their products and services accommodate the widest number of people possible" [Sharp, Rogers, & Preece, 2019]. In this context, designing a technology to be inclusive can mean considering users with sensory, physical or cognitive disabilities. It can also mean, more generally, designing for those who are often underrepresented.

Designing learning approaches for teaching new forms of computing to be inclusive for those with disabilities and impairments is in its infancy. Recent notable research has included the design of tangible interfaces that enables all children, including those with visual impairments, to code [Morrison et al., 2018], and coding clubs for people with intellectual disabilities [Koushik & Kane, 2019]. A focus of the research presented here is to extend this body of work further. However, it is not possible to explore all disabilities within the scope of this thesis. To begin, we focused on teenagers (16-19 years old) with special education needs (SEN). The reason for this was that that we were fortunate to have access to a special needs school that was keen to try out the technology and pedagogical methods that we were developing. Next, I describe the research that has been carried out so far on the challenges of teaching children in mixed SEN settings, and on how tangible and physical technologies might rise to meet these challenges.

Computing for children in mixed special education needs classrooms

14.9% of school-aged students in the UK are said to have special education needs [Department for Education, 2019]. In England alone, there are over one thousand government-funded and private SEN schools. Designing for all within SEN schools can be challenging, because learners often have a variety of special education needs, including Autism Spectrum Disorder (ASD), severe and moderate learning difficulties, as well as specific neurological impairments, such as acquired brain injury or sensory impairments.

However, although each specific special education need gives rise to a unique learning profile, it has been suggested that as a group, learners with SEN face a number of similar key challenges. These include difficulty in dedicating sustained attention to the task at hand, and difficulty with understanding and recalling abstract concepts [Falcão & Price, 2010]. Additionally, especially learners with ASD face challenges with a number of processes related to collaboration, such as recognizing the other as a partner in interaction and building and sustaining joint awareness [Holt & Yuill, 2014].

It has been suggested that physical and tangible interfaces, in particular, can be a suitable approach to teaching in these school settings [Falcão & Price, 2010]. This is because – as the previous sections have demonstrated – they can enable collaboration, provide concrete representations of abstract concepts, and provide opportunities for embodied interaction. These properties are hypothesized to support the common challenges that SEN learners face when learning. As such the Magic Cubes toolkit used in this research is hypothesized to have much potential for teaching computing to SEN students.

2.4 Summary

This literature review has showed how theoretically-motivated design principles have been applied to a variety of physical and digital interfaces to teach children about computing, especially with coding environments like Scratch and with tangible user interfaces. It has also showed how influential different theoretical perspectives have been in shaping the methods and approaches that are used to teach computing. Most notable are constructionist theories, discovery learning, and other kinds of hands-on activity where children can develop their understanding of abstract concepts by connecting them to public entities and embodied actions. The benefits of learning with others through collaboration were also discussed, and especially the value of collaborative learning in helping children reflect upon the properties of technologies and the principles of computing being learned.

More specifically, the literature reviewed discussed how programming environments for children have employed design principles based on constructionist learning theory, by using concrete "agents" that children can relate to, rather than abstract data structures, in order to enable body-syntonic reasoning [Papert, 1980]. It also showed the importance of designing meaningful learning experiences by encouraging interest-driven creativity [Resnick et al., 2009]. Moreover, it was seen how a wealth of TUIs have been designed using several general theoretically-motivated principles. Most prominent, was the idea of using tangible objects-to-think-with [Papert, 1980; Parkes, Raffle, & Ishii, 2008; Raffle, Parkes, & Ishii, 2004; Resnick, 1998] as a way of promoting concrete experiences and embodied interaction, when teaching children about abstract concepts. It was noted how the evaluations of these technologies have shown that most of the TUIs reviewed fostered collaborative behavior between children (e.g., [Horn, Crouser, & Bers, 2012; Johnson, Shum, Rogers, & Marquardt, 2016]). Additionally, several studies were successful in encouraging children to discuss and reflect on the concepts to be learned (e.g., [Hitron et al., 2019; Johnson, Shum, Rogers, & Marquardt, 2016; Zuckerman, Arida, & Resnick, 2005]), which was suggested to help them make sense of the underlying concepts instantiated in the activities. However, the evaluations of many of the technologies presented have tended to be somewhat high level, and have not fully explained what specific factors of the interface, and of the learning activity it is combined with, contribute to the observed positive effects.

An aim of this thesis is to address this evaluation gap, by adopting a more-fine grained analysis of what children do while learning. In particular the goal is to conduct a thorough investigation of how interaction with a tangible interface for learning about computing unfolds during the learning process. Based on the learning theories discussed, it is important to understand in more detail how different technologies for learning about computing support *cognitive activity* in situ, rather than just behavioral activity. Using a concrete, physical object in itself is not enough to foster learning about abstract computing topics. What matters is how this object is designed, what types of embodied interaction and collaborative activity it leads to, and how this leads children to reflect on what is being learned. Indeed, beyond the domain of teaching children about computing, there has been more detailed research into how different forms of technology influence learning.

To explain this, Antle and Wise [2013] proposed a detailed conceptual framework that comprised a set of design principles for effective TUIs based on theories from constructivism, constructionism, embodied and distributed cognition. In their framework, they provide specific empirically-motivated suggestions for triggering reflective activity through TUIs and their associated learning activities. These include manipulating the way in which information is presented to encourage reflection, for example by slowing down interaction (e.g., [Price, Falcão, Sheridan, & Roussos, 2009]) or pairing familiar input actions with unfamiliar effects [Rogers & Muller, 2006; Rogers et al., 2002]. Therefore, positive learning effects result from the interplay between the design of the form factor, the design of corresponding learning activities, and the way in which information is presented in relation to the two. However, there is still a need for more research on how these should be designed for the computing education domain. Therefore, within computing education, different forms of evaluation are needed in order to better explain how different aspects of the interface design, as well as the support structures embedded in the learning environment (e.g., the instructions and instructors) support the learning process. How this might be done is discussed in more detail in Chapter 3.

In terms of computing topics, the literature review has demonstrated that there has been empirical research into teaching children some aspects of IoT, like hardware and systems thinking. However, these have rarely been framed as components of IoT specifically, and indeed, there has been very little research on what topics are important to introduce first when teaching IoT. While the literature is rapidly emerging about what it means to teach IoT at the postsecondary level (e.g., [Burd et al., 2018]), there has been little written about how to teach younger children. Are the same suggested IoT topics suitable for them, for example children 8-12, who are just starting out learning about computing? If so, how can these topics be designed at an appropriate age-related level? This is a core question that this thesis aims to address. It will do so by using constructionist and constructivist theories to frame and operationalize IoT learning.

It was also found that what is lacking in this body of research was an understanding of how to teach computing as it becomes more extensive, covering not just learning to code but also a range of other concepts, such as privacy, cloud computing, data, and

IoT. All of these other aspects are equally important – and yet it is still unclear how to teach them in tandem, as well as when and how to relate the various aspects with each other, so as not to overwhelm the learner. In this thesis the four facets of learning computing are placed together, rather than viewed as separate as has been often been done to date: computational thinking, systems thinking, thinking about hardware and critical thinking.

In this way, it is argued that there is a need for more unifying, comprehensive frameworks explicating how the different aspects of modern computing relate to one another in practice. Where the aim of digital fluency, as a whole, is to move laterally between different topics and ways of thinking, it remains to be understood how learning approaches can be best combined to achieve this, as well as how they can be designed to support learning trajectories of this broader notion in the longer term. A broader aim of this thesis is to develop a conceptual framework that can be used to inform the design of new toolkits specifically for teaching computing concepts. It is proposed that this will provide a better understanding of, together with guidance on, how to teach digital fluency in the context of IoT. For the research conducted here, the Magic Cubes toolkit [Marquardt, Lechelt, Rogers, & Shum, n.d.] was used to investigate how this can be accomplished, specifically in the context of teaching IoT. This involves investigating how previous approaches like discovery learning and programming can be combined, as well as extended to teach about components of computing that are increasingly important, like thinking about hardware and critical thinking about new technologies.

Finally, another question that is addressed in this thesis is how the methods for learning about computing concepts can be designed to be more inclusive. Most of the approaches for teaching computing that were reviewed in the previous sections focused on designing for neurotypical children. The goal, however, should be to design for all children. Of interest here is whether children with different special education needs can capitalize on the affordances of TUIs when learning computing in the way neurotypical children have been found to. Moreover, can a curriculum be designed to in a way that is tailored to their particular needs? If so, how?

CHAPTER 3: LITERATURE REVIEW ON APPROACHES TO EVALUATING LEARNING ABOUT COMPUTING

The previous chapter focused on how theory from the learning sciences has influenced the design of approaches to teaching children about computing, and on identifying the gaps and potential for future approaches to teaching computing. Another fundamental question when developing new methods and toolkits for learning and putting into practice digital fluency is how to evaluate them. However, as was discussed in the previous chapter, there is currently a lack of standardized evaluation methods for assessing approaches to teaching about computing.

The focus in this chapter is therefore on the methods that have been proposed so far to evaluate and assess different aspects of learning about computing, in order to inform the methods chosen for the research in this thesis. While some of the methods discussed in this chapter have been directly related to assessing computing-specific knowledge, others are domain-general. I consider the evaluation and assessment methods in terms of two categories: *the subject* and *the method.* The *subject* pertains to the learning outcomes resulting from using a particular approach, specifically, the concepts and processes learned by partaking in an activity. The *method,* on the other hand, pertains to evaluating the particular approach itself. Under this category fall evaluations of the *usability* and *fun* of the approach, as well as evaluations of the extent to which the approach gives rise to types of interaction thought to support learning.

For the latter, I focus on assessing how *engaging* and *conducive to collaboration* the approach is.

3.1 Assessing the Subject

Several methods have been proposed for assessing children's understanding of computing concepts, and the extent to which an intervention helps them engage in particular types of thinking about technology. These range from post-tests, which often measure declarative knowledge acquired after participating in a learning activity, to more artifact-based approaches, which assume that computing is an active and situated process. By doing so, artifact-based approaches endeavor to measure how learners think and solve problems, beyond assessing their declarative knowledge. Below I consider each one in more detail, focusing on *post-tests*, *design scenarios*, *product-based evaluations* and *artifact-based interviews*.

3.1.1 Post-tests

A popular assessment method within the body of work on approaches for teaching children about computing is the use of post-tests (e.g., [Feaster, Zhai, & Hallstrom, 2015; Horn, Crouser, & Bers, 2012; Johnson, Shum, Rogers, & Marquardt, 2016]). These are administered after a lesson and usually comprise multiple-choice tests, measuring a child's understanding of specific concepts. Post-tests have several advantages, including the fact that they are easy for researchers to administer and analyze, and that they can potentially provide robust measures of changes in declarative understanding – for example, the extent to which a learning intervention improves a child's understanding of a specific computing concept. However, these types of traditional post-tests do not account for the fact that being 'digitally fluent' in computing relates not just to declarative knowledge, but also to the active and situated process of creating and thinking about digital products [Brennan & Resnick, 2012]. Therefore, if administered alone with no other measures, they are unable to describe the problem solving and thinking skills gained by learning through a particular approach. In sum, while these types of post-tests can be effective at assessing children's declarative knowledge of computing *concepts*, they do not explicate children's understanding of computing as a situated *process*.

An adaptation to post-tests, which does focus on analyzing computing as a situated process, has been proposed in the context of maker spaces [Davis, Schneider, & Blikstein, 2017]. Specifically, it has been suggested that the learning outcomes of participating in making practices can be measured by asking learners to carry out typical making activities, prior to and after participating in a maker space over a period of time. The proponents of this approach captured video of learners carrying out tasks like fixing a broken device or assembling a motor; they then coded the video data to analyze the ways in which the learners approached the tasks, in terms of how they planned their actions, carried the tasks out, and evaluated what they had done. By doing so, they gained rich insights into the way the learners' problem solving strategies changed before and after the intervention [*ibid.*]. This type of task-centered variation on post-tests therefore takes into account the thinking and problem solving processes that underlie digital fluency, that more traditional post-tests do not.

3.1.2 Design scenarios

Another task-based approach to assessing what has been learned about computing is through the use of design scenarios [Brennan & Resnick, 2012], where the emphasis is on evaluation-through-activity. This approach is similar to the task-based post-test approach described above, however in design scenarios, children are presented with a digital project that is related to the lesson that they previously completed. In the context of programming, for example, they can be asked how the project works, how a particular bug within the code can be fixed, and how the project might be extended. A design scenario, like a post-test, allows researchers to test for understanding of specific concepts. In addition, as a task-based method, it also allows for assessing other skills that go beyond declarative knowledge; in the context of programming, for example, design scenarios can allow researchers to better understand how certain learning technologies lead learners to develop their problem solving skills [*ibid.*].

3.1.3 Product-based evaluation

While many approaches for teaching computing involve asking a learner to create an artifact, it can be difficult to assess what the student has learned during the creation process. When this is the goal, it can be valuable to assess the artifact itself. Brennan and Resnick [2012] suggest that evaluating the knowledge of a learner by quantitatively measuring the techniques and concepts that they employ in their creations can be an appropriate method of assessing the scope and depth of their understanding. This can be fairly straightforward in particular when assessing computational thinking concepts from children's Scratch programs, where specific blocks of code relate directly to a computational thinking concept (e.g., conditionals, sequences, or events). However, like traditional post-tests, this type of product-based evaluation does not provide insight on a learner's thinking process [*ibid.*]. Because of this, it can sometimes lead to incorrect conclusions about the depth to which a learner understands something. For example through product-based evaluation, it could be concluded that a child who uses complex blocks of code in their Scratch project has highly developed computational thinking skills. However, an interview with the learner could later reveal that their creation is largely a product of "remixing" code from other users, and they do not understand the functionality of the blocks of code.

3.1.4 Artifact-based interviews

Another approach is to use artifact-based interviews. These also focus on an artifact created through the learning process, but reveal more about the *process* of creating the artifact, and allow for the identification of gaps in understanding [Brennan & Resnick, 2012]. In an artifact-based interview, a child is asked to present their completed digital or physical product to an instructor and discuss the process through which it was created, from ideation to development. This approach may be suitable for assessing the computational thinking process. Additionally, it is an assessment method that is highly contextual and meaningful to the learner.

However, it also has a number of limitations. First, it is time consuming, and one-on-one interviews with children in large group settings, like schools, are often infeasible for researchers to carry out. In response to this limitation, Portelance and Bers [2015] suggest peer video interviews, where, in pairs, children film each other explaining their creations. Children may also be more comfortable and less suggestible when speaking to their peers rather than adults, as being interviewed by adults who are perceived to be in positions of power can sometimes lead children to alter their responses in attempt to appease their interviewer [Bruck & Ceci, 1999; Read, 2008].

A second limitation with artifact-based interviews is that they heavily rely on the participants' memory [Brennan & Resnick, 2012]. Children might not remember, for example, at which point in their project they got stuck, and how they found solutions to problems. Additionally, a child may not utilize all of the computational concepts they know in a singular design, and so if the goal is to test the understanding of specific concepts, an artifact-based interview may miss some. For these reasons, an artifact-based interview is best combined with other evaluation methods, such as design scenarios.

3.2 Assessing the Method

Next, I discuss approaches to assessing four aspects of *methods* for teaching about computing. These include *usability*, *fun*, whether the method is conducive to *collaboration* between learners, and whether the method is *engaging* to learners. As seen in the previous chapter, these aspects are frequently reported on when describing the design rationale for approaches to teaching computing. This is because usability is key to ensuring that a learning approach is appropriate to the needs of the learner; fun, engagement and collaboration in turn are often considered to be integral to effective learning. Specifically, collaboration can trigger behaviors like discussion, which can lead to more reflection on the learning task; and fun and engagement are assumed to make the learner more attentive to the learning material.

3.2.1 Evaluating usability

In the early stages of prototyping a product, it is usual to assess its usability, or the extent to which users can use a product with effectiveness, efficiency and satisfaction [Jokela, Iivari, Matero, & Karukka, 2003]. This is to ensure unexpected issues do not arise during full-scale evaluations, as well as to provide opportunities to improve the design. While adult users can evaluate the usability of children's products, usability testing should ideally be carried out with the target audience [Druin, 2002]. In particular, it is important to take into account children's developmental and cognitive abilities, which might create usability issues that are not evident to adults.

Traditional usability testing methods can be adapted to be more suitable for children, by taking into account factors like children's capability to concentrate, their motivation, and their ability to provide trustworthy self-reports of a product's usability [Markopoulos & Bekker, 2003]. For example, one adaptation is the think-aloud method, which can equally be used by adults, where children verbally identify problems encountered while they use the product. It has been suggested that this method is more suitable for children than interviewing them after using a technology, as it lowers the amount of information that children have to recall, leading to more detailed reports of usability issues encountered [Baauw & Markopoulous, 2004]. However, it has also been suggested that children may often forget to think-aloud during the use of a product, and when prompted, may report non-problems in effort to appease the researcher [Donker & Reitsma, 2004].

3.2.2 Evaluating fun

An alternative approach to evaluating how well a technology for children is designed, beyond usability, is by evaluating how much *fun* children have while using it [Read, MacFarlane, & Casey, 2002]. Read, MacFarlane and Casey [2002] propose that the measures underlying traditional definitions of usability – like system effectiveness and efficiency – do not always reflect the goals that children's technologies aim to meet.

Fun, however, is often a core goal of children's technologies; simultaneously, fun can be viewed as a construct that is correlated with usability - for example, a poor experience with a product due to usability issues may cause a child's self-measure of how much fun they had using it to fall [Read, 2008; Sim, MacFarlane, & Read, 2006]. Therefore, when an enjoyable experience is a core goal of a technology designed for children, fun can be an appropriate construct to measure, for instance by asking children to report how much they enjoyed using a technology using a modified Likert scale, or by sorting which type of activity they found the most enjoyable from a set [Read, MacFarlane, & Casey, 2002].

3.2.3 Evaluating collaboration

Given that active collaboration and dialogue during learning can be useful for triggering reflection about the content to be learned [Dillenbourg, 1999], it is often considered important that learning environments are designed to engender collaboration. Within the domain of technologies for teaching about computing, researchers have used a variety of methods to analyze the extent to which collaboration between learners occurs when using a specific technology.

Many of these have looked at collaboration at a broad level. For example, in their study of children using a tangible programming interface at a summer camp, Horn, Crouser and Bers [2012] utilized what they called a "thank-you web". In the thank-you-web, children marked the pictures of all other peers with whom they collaborated during a project. While this could be a useful measure in a comparative study of two technologies, or when viewing the amount of collaboration as a dependent variable, it does not provide contextual information about the *quality* of children's collaborative interactions, and the extent to which the collaboration triggered cognitive processes related to learning.

Another approach has been quantitatively coding the amount of time children spend interacting in different ways during the learning process, for example, by working together to complete a task, showcasing their achievements to others and working independently [Johnson, Shum, Rogers, & Marquardt, 2016]. This is informative in terms of differentiating types of collaboration that can arise with a particular technology and evaluating the extent to which they occur. However, despite the fact that it provides more detail about the *type* of collaboration taking place, it still does not provide much detail about how the collaboration supports the learning process *in situ*, in terms of describing how children discuss and reflect on what is being learned while collaborating.

An approach that can be adopted that does address this entails more descriptive, qualitative coding of audiovisual data, focusing on the dialogue that children engage in while collaborating. For example, in their paper on collaborative tangible interfaces for learning programing, Suzuki and Kato [1995] describe analyzing children's dialogue together with non-verbal, embodied interactions to qualify *how* the type of collaboration that took place, supported learning. By using conversation snippets together with a description of the non-verbal, embodied interactions that children used, their analysis was able to show how the learners built and refined their plans of action through conversation, and the way in which they monitored each other's actions to learn how to use the technology together [*ibid.*].

Beyond the domain of teaching computing, this type of approach to describing collaboration, that is, focusing on how people's dialogue and non-verbal embodied interactions unfold over time, has increased in popularity, for example, in the computer supported collaborative learning community [Stahl, Koschmann, & Suthers, 2006]. A variety of methodological approaches can be used to analyze collaboration in this way, ranging from conversation analysis to Interaction Analysis [Goodwin & Heritage, 1990; Jordan & Henderson, 1995]. Adopting this type of qualitative approach – in lieu of the broader lens of *quantifying* how much collaboration occurs – provides different types of insights into collaborative learning as a process. Specifically, it can show how the type of collaborative activity that is engendered by a technology might influence cognitive mechanisms that support learning, like knowledge elicitation and reflection [Dillenbourg, 1999]. Therefore, it can be especially suitable when the goal is to understand *how* exactly a technology supports collaborative learning, rather than *that* it does.

3.2.4 Evaluating engagement

It is often assumed that an active learning process, and an engaging task can be more conducive to deeper learning. The question is how to measure this? Choosing a method to evaluate engagement, like choosing a method to evaluate collaboration, is dependent on the research question as well as the way in which the construct of engagement is defined. In literature on teaching children about computing, engagement is sometimes used as a proxy for enjoyment. Alternatively, the term engagement can refer to *cognitive* engagement, that is, the extent to which a learner sustains mental effort while learning [Corno & Mandinach, 1983; Price & Falcão, 2011].

Some researchers that have used engagement as a construct related to *enjoyment*, have evaluated engagement by measuring the length of time that children interact with a particular technology, under the assumption that more time spent interacting is related to a more engaging experience (e.g., [Horn, Crouser, & Bers, 2012]). Others, like Johnson et al., [2016] have used a "smiley-o-meter" (based on [Read, MacFarlane, & Casey, 2002]), a Likert-type scale of smiley faces, to evaluate how much children enjoyed interacting with a technology; this type of analysis is based on the assumption that higher enjoyment correlates with higher engagement. Another method that has been suggested has been to observe body language that suggests concentration, enjoyment or negative affect – for example coding how often children smile, yawn or frown while they partake in an activity [Read, MacFarlane, & Casey, 2002]. Though this type of method has been suggested to be informative when comparing levels of engagement between different activities for the same child, it has been found to be uninformative when used to monitor engagement for only one task, between different children [*ibid.*]. The reason for this is that different children may not demonstrate how they feel using their body language in the same way [Read, 2008].

It has been suggested that in the context of evaluating learning experiences, viewing engagement through the lens of enjoyment is not necessarily indicative of how successful a technology is for fostering learning [Price & Falcão, 2011]. This is because the methods described above do not provide much detail about the learning process itself, in terms of what children do and think while engaging in a learning activity. Specifically, children enjoying an activity or interacting with a technology for a long period of time does not necessarily mean that they are focusing on the learning-relevant aspects of the activity. Alternatively, engagement can be characterized as a state of active participation in a lesson [Astin, 1984]. When viewed through this lens, it can be characterized by the amount of concentration and effort learners put into a learning activity [Marks, 2000]. This type of *cognitive* engagement has been said to be observable by analyzing how and to what extent learners sustain attention to a task that requires mental effort [Corno & Mandinach, 1983; Price & Falcão, 2011].

Viewing engagement through this lens lends itself to analyzing how engagement contributes to a technology's efficacy in supporting learning in a more nuanced way. For example, Price and Falcao [2011] propose an analytical framework for analyzing the different ways in which children engage with a discovery-based technology for learning. Their framework suggests coding instances of children focusing their attention on (i) how the technology they are using works, (ii) engaging with the domain learning concepts and (iii) exploring the technology without necessarily focusing on the domain learning concepts.

Price and Falcao [2011] applied this framework to a discovery-based task where children learned about physics of light (specifically how light is absorbed and refracted) and qualitatively examined how each of the three foci of attention contributed to the children's overall learning process. In this way, they were able to show how each type of focus of attention contributes to the holistic learning process in a different way. For example, they found that exploring the technology in an open-ended way, without focusing on the learning domain concepts explicitly, provided the children with a level of scaffolding about how the system worked, that they drew upon when later discussing the concepts explicitly – i.e., how light is absorbed and refracted. Focusing on the technology itself, in turn enabled the children to observe when it broke down; this then contributed to spontaneous reflection about the domain learning concepts. This type of analysis of engagement, which seeks to clarify the different aspects of a task that children focus on when learning, and how they contribute to *cognitive engagement* – can therefore lead to a more robust understanding of how to effectively design both the technology itself, and how to structure the learning activity to enable children to reflect on what they are doing and learning.

3.3 Summary

As this chapter has demonstrated, a variety of methods can be used to assess the extent of children's learning about computing or other topics, as a result of interacting with a technology, as well as how usable, engaging and conducive to collaboration the technology itself is. The literature reviewed suggests that when choosing an approach to assess learning outcomes, it is important to take into account that computing is a situated skill to be learned, rather than one only concerned with declarative knowledge. This has implications on the choice of assessment methods used with learners; for example, using only post-tests that measure understanding of concepts, does not account for the situated nature of computing, which involves processes like breaking down and solving problems. Similarly, only looking at the artifact that an individual has created, does not explain the extent to which they understand the computing concepts in an artifact. This suggests that to measure learning outcomes in the context of computing, it is important to focus on methods that are *task-based* and *process-based,* and that can shed light into learners' situated problem solving, rather than just how much declarative or conceptual knowledge they have gained.

As the section on assessing the method has shown, there have also been a variety of approaches to assessing the usability of a children's technology, and the extent to which it is engaging or conducive to collaboration. The literature demonstrates that usability, collaboration and engagement are not straightforward, one-size-fits all terms. For instance, engagement is often assessed by measures of enjoyment or how long children interact. These approaches, however, do not necessarily provide insight into the efficacy of the technology for fostering *cognitive* engagement – which is important to the learning process. Cognitive engagement, rather, goes together with more qualitative, in-depth approaches that address what learners focus on when interacting with a technology, and how they discuss what is being learned.

Similarly, deciding on the type of approach to employ when evaluating how collaborative an interface is, is dependent on the research question. For instance, seeking to understand *how* collaboration supports the learning process requires a different methodology to analyzing just *whether* a technology supports collaboration. The former question requires a fine-grained analysis, which calls for an analysis of how the collaborative process unfolds over time, and how it leads learners to discuss and reflect on what is being learned. However, this type of approach is not frequently employed within the domain of approaches to teaching computing, specifically; work has often instead focused on the former question of *whether* the technology is collaborative, often by quantifying collaboration.

In sum, this chapter has demonstrated how when choosing an approach to evaluating how effective a learning approach is to teaching children computing, it is important to take into account that computing is a process that is linked both to conceptual understanding and more lateral thinking about technology. The studies reported in this thesis, therefore aim to provide more multifaceted, detailed and descriptive measures of how the learning process unfolds when learning about computing, and which is in line with learning theory. One approach is to use a mix of methods that measure multiple ways of thinking—for example, by combining artifact-based interviews with design scenarios. Another approach is to examine how hypothesis generation and reflection about the target learning concepts arises throughout the learning process through a more fine-grained analysis of collaboration and interaction. The research reported in this thesis predominantly takes the latter approach, so as to be able to investigate how more detailed, micro-analytic methods of assessing aspects of the learning process can be applied to the domain of computing education. The next chapter, which focuses on the methodological approach adopted for this research, discusses this in more detail.

CHAPTER 4: METHODOLOGY

Today coding and computational thinking are being taught to children from an increasingly young age, however there is still a need to define best practices for incorporating emerging technology paradigms into computing education. In particular, the literature reviewed demonstrated that while there is emerging work on teaching IoT in higher education, the topics that IoT education should include for children in primary and secondary school are still ill-defined. Moreover, while there has been research on teaching children some topics that relate to IoT, such as hardware and systems thinking, these have rarely been framed as components of IoT specifically. Thus, there is still a need to understand what topics are important to introduce first when teaching IoT, and how this can be done.

A core aim of this research is therefore to address the questions of how to operationalize, implement and evaluate the first steps for teaching schoolchildren about IoT. Specifically, the goals are 1) to investigate what topics primary and secondary IoT education should include, 2) to design and evaluate learning activities that facilitate learning about these topics in school and informal settings, and 3) to investigate how learning about IoT can be made accessible and inclusive. This chapter describes the methodological approach chosen to address these research questions, and the motivations behind the choice of methods. Specifically, a number of qualitative methods were used, including interviews, workshops with experts, user-centered design, reflection and in the wild, video-based research.

4.1 Research Process: A Three-Phase Approach

The research questions are addressed using a three-phase research approach. The phases are: 1) developing a foundation of IoT topics, 2) iterative, design and prototyping of learning activities, and 3) in the wild research to evaluate the designed learning activities in formal and informal settings. By learning activities is meant the coupling of technology (i.e., a physical toolkit), associated learning tasks and instructional techniques. The user group chosen for this research is predominantly primary school children, specifically ages 8-12. This group was chosen as it maps to the age in the UK computing curriculum where students begin learning about computing concepts like the relationship between hardware and software, computer networks and safe and responsible use of technology [UK Department of Education, 2016]. Although the learning activities developed as part of the research were not designed with meeting existing, specific curricular aims in mind, it was decided that IoT topics could complement these broad curricular goals for this age group. However, it was also considered important to make the learning activities accessible to wider audiences; therefore, the research also considers how to make computing education more inclusive, by reaching out to other groups – including older students, aged 16-19 with special education needs, and the broader public, comprising children and teenagers of all ages.

The three phases informed each other throughout the research. For example, the IoT topics identified serve as a starting point for developing learning activities and for considering how best to evaluate them. Moreover, throughout the research, the learning activities were iteratively designed and evaluated; in this way, the design and evaluation phases feed into each other.

The evaluation of each study also led to new research questions – for example, the first video-based study (Chapter 7) focused on how children capitalize on embodied interactions and turn taking when interacting with a physical toolkit to learn about how sensors and actuators function together. The findings revealed much about how the children used embodied interaction to negotiate collaboration and comprehension; they also showed that the children exhibited curiosity to learn more about the data that was sensed. This in turn led to the formulation of the next research question, of how to enable children to partake in higher-level critical thinking about sensed data.

Figure 4.1 describes the methods used in each of the three phases. The next sections then describe and motivate the methods followed in each of the three phases in more detail, together with a description of the reasons for using them and their theoretical assumptions.

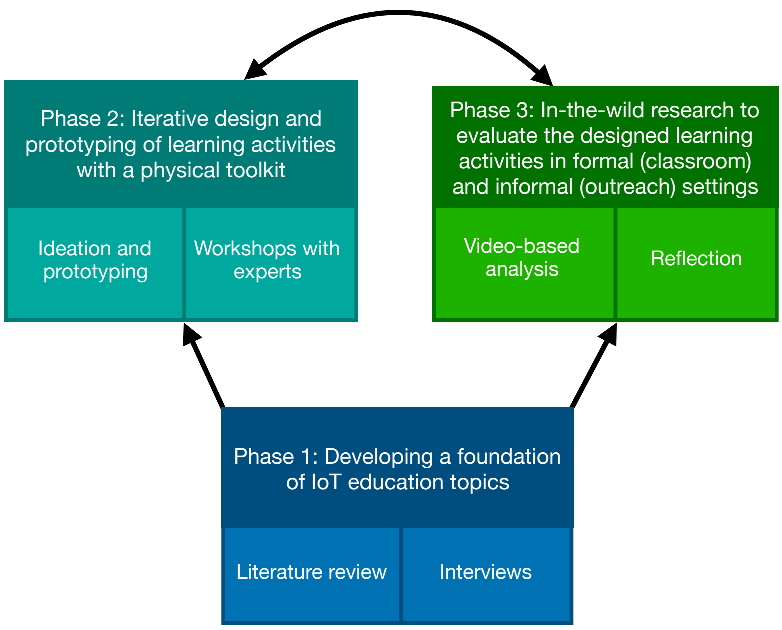


Figure 4.1: The three-phase methodological approach.

4.2 Phase 1: Developing a Foundation of IoT Education Topics

In order to develop a set of topics that might be taught as part of IoT education, first, literature was reviewed about the current practices for teaching about computing (Chapter 2). This revealed that while there is emerging work on teaching IoT in higher education, there has so far been little research addressing how to teach children in primary and secondary schools about IoT within the context of how IoT is now becoming an everyday technology in our lives. Moreover, it was found that the topics that IoT education for children should include are still ill-defined. The first research question to be answered was, therefore: *what IoT topics are suitable to teach in primary and secondary schools?*

Beginning to answer this question required exploratory work. For this reason, it was decided to carry out interviews with people with a diverse range of experiences with IoT. Specifically, six participants were recruited from a variety of professional backgrounds related to the IoT; two participants were IoT designers, two were in the Maker Movement with a special interest in IoT, and two were university-level IoT educators. This selection was chosen because it was considered important to gather a diversity of perspectives on IoT and IoT education.

Because the interviews were exploratory in nature, they were semi-structured to give participants the opportunity to elaborate on their responses. The analysis was carried out using the thematic analysis method [Braun & Clarke, 2006]. Specifically, the interviews were transcribed and the data was coded. This was done through an inductive, data-driven approach where codes were created through iterative, bottom-up review of the data with no *a priori* coding scheme. Finally, themes were identified by cyclically examining and grouping the codes. The outcome of this method was a set of themes demonstrating what topics might be suitable to teach to children as part of an IoT curriculum. These included, for example, the functional mappings between sensors and actuators, simple networked systems, and critical thinking about data. The next questions to be addressed are how to teach these topics and how to evaluate the teaching methods. To explore further how a subset of IoT topics could be taught to primary school children, it was decided to follow an iterative design approach to prototype learning activities together with a physical toolkit.

4.3 Phase 2: Iterative Design and Prototyping of Learning Activities with a Physical Toolkit

The literature reviewed showed how hands-on activity afforded by tangible interfaces and physical computing toolkits can make learning about abstract computing concepts engaging, as well as lower the entry threshold to learning about complex computing topics. Moreover, the outcome of the interviews suggested that hands-on exploration of electronic components might enable children to not just understand the functionality of IoT hardware, but also to begin thinking critically about its limitations. For example, it was suggested that tinkering with and testing data sensors might be used as a first step towards learning to reflect about their properties, such as their reliability and accuracy. For these reasons, it was decided to approach the problem space by designing IoT learning activities together with an existing physical computing interface: the Magic Cubes. This was done through a user-centred design approach, which included ideation, prototyping and design workshops with HCI experts.

Many of the chosen IoT topics were considered to be conceptually complex for children (e.g., systems thinking concepts), and the focus of the design and prototyping stage was to investigate how to convey them to children in a way that is engaging and easy to understand. For these reasons, in the first design stage, it was decided to involve interaction design experts who were experienced with conducting research with and for children in the design workshops, rather than involving children directly. The children instead were recruited to partake in the evaluation phases, which in turn, fed back into the iterative design.

4.3.1 Ideation and prototyping

As a first step, for each of the IoT topics proposed for teaching IoT to children, new learning activities were ideated and prototyped. Ideation and prototyping involved conceptualizing the learning tasks, with respect to how the interaction with the physical computing interface would enable children to learn about a specific IoT topic. Equal emphasis was also placed on developing the materials that accompanied the learning tasks, and considering the learning environment in which they would be carried out. By this is meant, for example, considering how the instructions would be presented (e.g., on paper, verbally or both), and in what level of detail, as well as considering how much teacher support would be available in the classroom setting. The reason for placing such an emphasis on these factors from the beginning stages of the prototyping process is because a large body of literature has demonstrated the importance of considering the type of instruction (e.g., guided vs. unguided) and the learning environment (e.g., formal vs. informal) on learning outcomes (e.g., [Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Hmelo & Guzdial, 1996]). The specific prototyping techniques that were used included sketching the details of learning activities, developing instruction sheets, and prototyping the activities by programming the physical computing interface.

4.3.2 Workshop with interaction design experts

In the initial stage of design, a workshop with experts was used in between ideation and prototyping iterations. This was done because it was considered important to 1) test and evaluate new ideas for learning activities with interaction design experts experienced with research with children and 2) to gather new ideas, by asking the participants to ideate design alternatives and suggestions.

In the workshop the participants were presented with the initial prototyped materials and activities that were planned for children, and asked to complete the learning activities themselves. They then participated in a feedback session, where they discussed what they thought of the learning activities, especially in terms of how easy they were to understand and how engaging they were. The workshop ended with an ideation phase, in which the participants contributed insights about how the activities could be modified or redesigned. Reflective notes were taken during the workshop; subsequently, the participants' feedback and ideas were incorporated into the next prototyping iterations. This was found to be beneficial in particular for challenging the assumptions of the researcher, especially in terms of how easy or difficult the learning activities were to understand, and in terms of how the design of the instructions influenced engagement in the learning activities.

4.4 Phase 3: Research In The Wild to Evaluate the Designed Learning Activities

After the workshop, based on the insights accrued, new learning activities were iteratively designed and prototyped. The next goal was to evaluate them, in order to analyze whether and how they contributed to children's learning about IoT-related concepts. More specifically, the goal was to gain an understanding of how children learn and discover IoT concepts in situated settings. For this reason, a *research in the wild* approach was adopted throughout the thesis.

Although a core focus of the research is on how IoT learning can take place in schools, it was also considered important to consider how it can unfold in informal contexts, in particular at after-school coding sessions and at public exhibitions. This is because computing education is not always constrained to formal learning environments, and increasingly happens in extracurricular contexts. However, it was not considered appropriate to use the same evaluation approaches in the informal settings as in the school settings, because the former are not controlled and vary from one participant to another – as to how long they stay, what they expect and what they do. The instructions and activities offered in the informal settings were also adapted to the particular context. For these reasons, different methods were used to evaluate the designed learning activities in formal and informal settings. Specifically, video-based analysis of the learning process was conducted in classroom settings, whereas observations combined with a reflective stance were used to evaluate the extracurricular and outreach sessions that were held in various public spaces.

By a reflective stance is meant taking notes by the researcher about how people interact with the learning activities, as well as the pragmatic issues of deploying the physical toolkit in the wild. These were used to understand how the learning activities worked in practice in the different settings, and to consider at a broad level, what factors made specific learning activities with the physical toolkit engaging, as well as what features of the designs made specific concepts easier or more difficult to understand. These observations were also triangulated with reflective interviews from the UCL engineering outreach coordinator, and a UCL researcher who is active in teaching computing to children through outreach activities.

In contrast, the research that was carried out in the formal school settings was approached through using video-based analysis that focused on the learning process. Here, the aim was to evaluate in depth how the physical toolkit and associated learning materials work in real school settings, and how learning about IoT can unfold in the socio-material context of the classroom. An important research question that was addressed was how the collaborative and embodied nature of a tangible, physical computing toolkit can be exploited to good effect when learning about IoT. The outcome of the video-based analysis was a detailed, descriptive account of what children did when completing the various learning activities, especially in terms of how they explored the physical toolkit through embodied interaction, and how they collaboratively discussed IoT concepts.

4.4.1 Research in the wild

By *research in the wild*, is typically meant a broad approach to carrying out research in naturalistic settings, which is agnostic to specific methods or technologies [Yvonne

Rogers & Marshall, 2017]. This approach was chosen here because, in contrast to more experimental paradigms in lab settings, research in the wild places a central importance on recognizing that human cognition is complex; it is distributed, situated and embodied [Hutchins, 1995]. Because of this, it is particularly suited to HCI research where the goal is to provide insights into the interplay between the environment, technology and behavior which would not be readily observable in more controlled settings [Rogers et al., 2007]. As the research reported here was concerned with understanding how to design technology to support children's situated learning, it was decided that using an in the wild approach was most appropriate. Specifically, it provided an ecologically valid understanding of children's interactions with technology within the social and environmental contexts typically associated with both classroom and informal settings, where a variety of tacit and embodied social rules, as well as the physical space itself, are at play [Antle, 2009].

A downside of conducting research in the wild is that it shifts the locus of control away from the researcher, making it difficult to isolate causal relationships between variables of interest due to confounding factors that might be controlled in a lab setting [Rogers, 2011]. However, as the focus of this research was to characterize the interactions between the context, technology and behavior, it was less important to try to tease out the effects of individual variables. Moreover, as emphasized by Rogers et al. [2007], in the wild research is primarily concerned with providing descriptive *understandings* rather than isolated *results* that strictly support or reject a hypothesis. Therefore, in the wild research goes hand in hand with qualitative analysis methods that can provide rich descriptions of human interaction with technology and the environment.

4.5 Video-based Analysis of the Learning Process in Classrooms

Three evaluation studies were carried out in schools. The goal was to elicit a detailed understanding of how the children interacted with each other and with the materials when learning. This was because it was considered important to understand how the designed learning activities, together with the physical computing interface, contributed to the *learning process* rather than just the *learning outcomes*. The specific analytic questions in each school study and the analytic frameworks used to address them evolved in tandem throughout the research process.

4.5.1 School Study 1: The role of embodied interaction during collaborative discovery learning

In the first school study (Chapter 7) the goal was to examine whether and how children would capitalize on the tangibility of the physical computing toolkit in order to collaboratively build an understanding of the functionality of its electronic components. To address this, the video analysis focused on how the children's 'embodied interactions' mapped to their learning process as they interacted with the physical toolkit. By embodied interactions in this context was meant gestures relating to turn taking and collaboration—for example, grabbing the toolkit from a partner, or interacting with the toolkit together with a partner. The need to understand how children collaborated with each other and the teacher was considered central to helping them learn new IoT concepts, as it has been found to facilitate learning about abstract concepts [Dillenbourg, 1999; Suzuki & Kato, 1995]. Hence, the focus of this study was on identifying and describing the collaborative and embodied interactions that occurred in the classroom, rather than on measuring specific learning performance or knowledge outcomes.

4.5.2 School Study 2: Promoting critical thinking about sensors and sensing

A question that evolved from the findings of the first study was how critical thinking about IoT topics, like sensor data and the act of sensing might be supported during the process of collaborative and embodied learning with the physical toolkit. To address this aspect, the focus of the next school study conducted (Chapter 8), was more on the school children's dialogue with both their peers and teachers, and how this mapped to their embodied interactions during the process of discovery learning. Analyzing the dialogue that arises during the learning process can provide a detailed understanding of how a learning approach influences sensemaking and abstraction [Stahl, Koschmann, & Suthers, 2006]. Therefore, the approach adopted here was assumed to provide more insights about the kinds of learning processes that occur when moving from hands-on activities using physical artifacts during discovery learning, to a higher level understanding of abstract concepts used in critical thinking. This approach elicited a description of the contexts in which critical thinking about IoT can unfold.

4.5.3 School Study 3: Learning about IoT over time in a special education needs setting

A question that arose from the second study was how inclusive the approach being proposed for learning IoT concepts was. A second question was how learning about IoT with the physical toolkit could be supported over time, beyond one off sessions. The aim of the third school study (Chapter 9) therefore addressed the topic of accessibility of learning about IoT by examining whether the collaborative behaviors, comprehension and engagement that were observed in the first two school studies would also arise in a Special Education Needs (SEN) school context. A further goal was to understand if interacting with the physical toolkit for different activities could extend the kinds of learning about IoT over a longer period of time. Therefore, the third study investigated how a different group of students – 16-19 year old students in a SEN classroom – could learn about basic IoT concepts using the toolkit over a period of six sessions during one term. For this study, a different analytic lens was used. Specifically, the focus was more on the learning that took place over a period of time by comparing how the SEN students collaborated and sustained their attention during the sessions over several weeks. It also concerned how different activities designed for interacting with the physical toolkit supported learning in this context.

4.5.4 Data collection methods used

The main data collection method chosen for all the formal school studies was the use of video and audio recording. Video-based research is recommended as a means of analyzing embodied and collaborative interactions, especially as it provides the opportunity to repeatedly scrutinize naturalistic video to understand how interaction unfolds over time, and how interaction is influenced by the socio-material context [Heath, Hindmarsh, & Luff, 2010]. Jordan and Henderson [1995] describe how even a trained researcher may miss relevant observations in a busy naturalistic setting, and how the ability to watch and analyze video segments repeatedly can enable the researcher to better understand complex interactions and phenomena. This property of video data was considered especially important in the classroom settings in which this research took place, where often 20-30 children were interacting simultaneously.

4.5.5 Analysis methods used

The approaches adopted to analyze the collected data varied across the three school studies, but were all based on the foundations of *Interaction Analysis* (IA). IA is a general, ethnographically-informed approach, that seeks to understand how people interact with each other and with their environment in situated contexts, through iterative examination and categorization of audiovisual data [Jordan & Henderson, 1995]. The methodology adopted was based on IA due to its emphasis on situated interaction, which was the core focus of the evaluation studies. Specifically, a fundamental assumption underlying IA is that knowledge and interaction are rooted in social and material ecologies; therefore, IA crucially considers not just talk, but also factors like embodied conduct and physical interaction with artifacts and materials. For example, analyzing children working together on a computer using an IA lens, enables the researcher to examine how turn-taking manifests itself through the body and actions on the artifact, such as the taking and relinquishing control of a mouse [*ibid.*].

The audio and video data in the school studies was examined through a combined micro- and macro-analytic lens. By micro-analysis is meant an in-depth coding approach that focuses on characterizing micro-segments of data, for example single lines of talk, or singular embodied interactions like grabbing or handing over an artefact [Strauss & Corbin, 1998]. Strauss and Corbin posit that focusing on these types of micro-segments of data, can enable the researcher to better understand how and why interaction arises in a specific way than just looking at broader patterns of interaction over time [1998]. For instance, interrogating the data in this way can help the researcher ask questions about the purpose of participants' dialogue or gestures in a particular context. Moreover, micro-segments can reveal phenomena that may not be visible from using a purely macro-level analysis of data (see e.g., [Price & Falcão, 2011; Wise et al., 2015]). In contrast, a macro-level analysis provides a broader understanding of how the process of interaction emerges and changes over time – for example, over the course of a 60-90 minute classroom session. When used together, micro- and macro- levels of analysis can provide insights at different levels of granularity of how the affordances of the technology – in this case the physical toolkit – are used in embodied and collaborative ways.

At a procedural level, to analyze the audio and video data for each study, content logs were first created of the collected data. Subsequently, subsets of the data were iteratively examined together with other researchers familiar with the studies in order to decide on analytic foci and coding schemes. Identifying specific analytic foci then helped select smaller segments of data to be used for further analysis. The selected segments were then coded line by line, at a micro-analytic level. In study 1 (Chapter 7), the micro-level coding focused on collaborative embodied interactions (e.g., grabbing or handing over a cube). In studies 2 and 3 (Chapters 8 and 9), the focus was both on talk and on individual embodied interactions (e.g., jumping or reaching with a cube in hand).

A key focus for all of the studies was to examine how micro-analytic events evolved over time, and how they mapped onto the broader learning process. Hence, the coded data (e.g., segments containing codes of how children handed over the physical toolkit when discovering a sensor-actuator effect) were also examined in the context of when they occurred during the learning process, at a more macro level (e.g., moving from partially to fully understanding a sensor-actuator effect). In sum, micro-level events were triangulated with descriptions derived from the macro-level analysis to determine what learning took place, and to identify any specific patterns that occurred. Together, the analysis provided a comprehensive, descriptive account of how children used embodied cues, and conversational events to build a shared knowledge space, collaborate with others, and to critically reflect on the domain concepts.

Which video snippets to use from the hours of video data collected?

A key issue arising from adopting a video-based approach was to decide which data to select for analysis. Each of the three in the wild studies in this research created a large corpus of video data. For example, in study two (Chapter 8), a total of 86 children were recorded for 60-90 minutes each. Due to time constraints, it was not possible to analyze all the data collected for each study at the micro-analytic level, and as such decisions had to be made as to how to reduce the data. To address this, the amount of data to be analyzed was reduced through empirically recommended practical guidelines. Selecting which parts of video to analyze is contingent on the research question and level of detail to be analyzed [Derry et al., 2010; Heath et al., 2010]. Here, content logs were created of the video corpora, and data to analyze was selected based on guiding research questions and analytic frameworks, which differed in each study. Study 1 focused on instances of embodied interactions related to turn taking, study 2 focused on evidence of critical thinking, and study 3 focused on evidence of collaboration, engagement and comprehension.

4.6 Reflective Evaluation in Informal Learning Settings

Teaching IoT does not need to be restricted to just school settings. Workshops, extracurricular classes and hackathons are equally important venues for opening children's minds up to new topics and ways of learning. To this end, it was decided to see how IoT concepts could be also taught in a variety of informal learning settings. For this reason, throughout the research, in addition to being evaluated in school settings a variety of learning activities with the physical toolkit was tested in a number of outreach contexts. Because of the success of running an initial outreach session (as indicated by the feedback from the children, teachers and organizers), we were asked to run many more of these events throughout the three years of the PhD. These varied widely in terms of where they took place and who took part. For example, a number of the sessions were held as part of after school computer science outreach programs for children and teenagers, while others took place at festivals and conferences with families, teachers, or Human-Computer Interaction researchers.

Because the outreach sessions were in public settings, it was decided that the process of acquiring participant consent would have detracted from the interaction, especially in drop-in sessions where often more than 100 participants interacted with the learning activities for only a few minutes at a time. For this reason, it was decided to take reflective notes at each session, rather than try to collect any video or audio data - which requires consent from the participants. The reflective notes comprised anonymized, general observations about how people interacted with the activities, and what topics and ways of interacting they found to be engaging or difficult to understand. Moreover, they focused on the pragmatic issues of deploying the physical toolkit in the wild, as well as on the perceived social factors contributing to how participants interacted with the learning activities. For example, a key focus was on observing differences in how people interact in informal, unstructured settings (e.g., festivals) versus more structured settings (e.g., classroom sessions), and deriving implications for design of learning activities from these insights. In addition to the reflective notes, interviews were carried out with two individuals at UCL who were present at (without involvement) many of these outreach sessions over the course of this research, as well as had extensive experience with public outreach. The interviews were used as a way of gathering an additional source of feedback about what worked and what did not. In this way, the public outreach sessions were found to be an invaluable way of eliciting an understanding of how the learning activities worked in practice, and how IoT teaching might be modified to suit contexts varying from 5-minute engagements with families, to three-hour long extracurricular classes with teenagers. Chapter 10 describes in more detail the role of public outreach in this research.

4.7 Ethical Approval for the Studies in this Thesis

All studies involving human participants were cleared by university ethics boards. Specifically, the research presented in Chapters 5, 6, 7, 8 and 10 was conducted under UCL Ethics Project ID Number 8077/001. For the study presented in Chapter 9, which was carried out in a special needs school, we collaborated with researchers from the Children and Technology Lab at the University of Sussex, who were experts in research with children with intellectual disabilities. For this study, the ethics approval was obtained by Prof. Nicola Yuill of University of Sussex, under the code ER/NICOLAY/9.

4.8 Summary

The methodology adopted in this thesis was primarily qualitative and design-focused. The goal was to develop a new understanding of how children learn about IoT concepts through hands-on discovery activities, together with determining how best to design learning activities using a physical computing toolkit. The methods used were mixed, including interviews, user-centered design methods, reflection and in the wild, video-based research. This enabled a diversity of insights to be gleaned about how learning about IoT can be supported in different learning contexts. The contribution of the research is a detailed, descriptive account of how children and teenagers, from a variety of backgrounds and ages, can learn about introductory IoT topics within primary and secondary computing education. The findings demonstrate how learning activities for teaching IoT topics can be designed to contribute to *collaborative and embodied interaction*, *hypothesis generation*, and *critical thinking* for a variety of learners in informal and formal settings.

CHAPTER 5: INITIAL STUDY ON INFORMING A NEW IOT CURRICULUM FOR 8-12 YEAR OLD CHILDREN

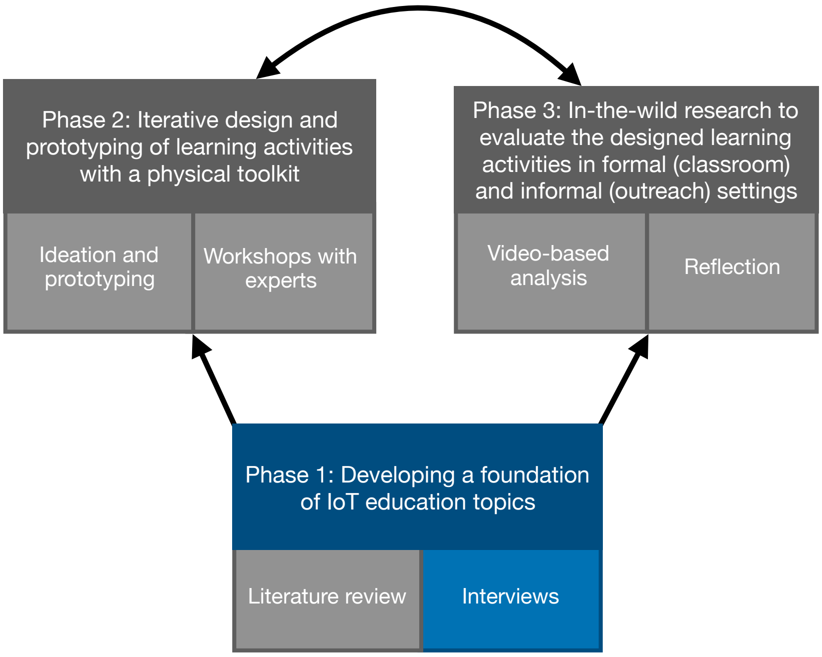


Figure 5.1: This chapter presents interviews with IoT experts to develop a foundation of IoT education topics for schoolchildren.

As demonstrated in the literature review, there has been little research explicitly investigating how to teach children about IoT. Where research has been carried out about what topics are important to introduce when first teaching IoT, this has largely been at the level of higher education. As a first step to address this gap, it was deemed important to begin mapping out both *what* IoT topics might be appropriate to incorporate into primary and secondary curricula and *how* this might be done. Initial interviews were carried out with a number of people from a broad range of backgrounds within IoT, including post-secondary educators, IoT makers, and IoT designers in industry. This enabled a variety of perspectives to be obtained.

The interviews were conducted in order to find out what IoT professionals think are suitable topics that need to be taught about IoT to children at the end of primary school and beginning of secondary school just starting to learn about computing (i.e., those aged 8 years and upwards). The interviewees' answers were analyzed to identify what were perceived to be the motivations for teaching children about IoT, and to explore what to teach and how. This chapter discusses the findings from the interviews, which are subsequently used throughout this thesis to inform the design and evaluation of learning activities. A main finding was that the participants suggested two types of interrelated learning outcomes to consider when deciding what IoT content to teach: (i) *higher-level thinking* and (ii) *conceptual understanding* about IoT. A number of suggestions were also provided about the types of learning activities that can be designed to teach IoT topics, by capitalizing on hands-on exploration of physical hardware, and on personally meaningful content that enables children to reflect on their relationships to IoT data.

5.1 Methodology

5.1.1 Participants

Six individuals were recruited to take part in the interviews. The participants were selected based on the researcher's familiarity with their work and chosen on the basis of their professional backgrounds, where the goal was to gather a variety of perspectives. Two of the participants (*U1, U2)* had experience in teaching IoT at the university level, three had experience in designing and running informal workshops related to IoT (*M1, M2, D1*), and all but one of the participants (*U2*) had some experience in industrial design and engineering for IoT technologies. Table 5.1 summarizes the participants' primary domains of expertise:

Table 5.1: The participants' primary domains of expertise.

Participant	Primary Profession / Domain of Expertise
D1	Product designer for IoT, maker
D2	Designer and engineer in the research department of a large corporation
M1	Multidisciplinary maker and organizer of interdisciplinary events that connect people and technology
M2	Multidisciplinary artist and maker
U1	University educator in IoT, engineer in industrial IoT
U2	University educator in IoT, based in the United States

5.1.2 Procedure

Five of the individuals were interviewed in person in informal settings, and one (*U2*) was interviewed through a video call. Due to their preference and availability, *D1, M1* and *M2* were interviewed together as a group, while participants *D2, U1* and *U2* were interviewed individually. The interviews were semi-structured with two main points of focus. The first focus related to the participants' backgrounds with IoT, and what they perceived "IoT topics" to be. Specifically, the participants were first asked to discuss how their work and interests related to the IoT. They were then asked to define and discuss their perceptions of what "IoT topics" are, using examples of existing technologies.

The second focus of the interviews was on how IoT topics might be incorporated into a future computing curriculum. In this part of the interview, the participants were asked questions about what they thought people, and specifically schoolchildren, should know about IoT. The participants were told that the age group considered for the research was mainly children ages 8 to 12. Furthermore, they were asked about what they perceived to be the benefits and barriers of introducing IoT topics into the computing curriculum. Because the study was exploratory, the interviews were semi-structured to enable the participants to elaborate on their responses. The participants were also asked to share their current experiences with teaching about the IoT or teaching using IoT technologies.

5.1.3 Data analysis

The audio recordings of the interviews were transcribed. During the process of transcription and familiarization with the data, it was found that a number of topics were mentioned by the participants in more than half of the interviews. Because of their prevalence, these topics were identified as themes to be included in the findings. For example, all six participants discussed how learning to think critically about new technologies should be a key part of computing education. Teaching critical thinking was therefore considered as a primary motivation for teaching IoT. Next, the data was methodically coded, and the codes arranged into themes through inductive thematic analysis [Braun & Clarke, 2006]. For example, the coding revealed that several participants provided examples of public misconceptions about IoT technologies. These instances were collated under the theme of 'promoting realistic perceptions and expectations for technologies'.

5.2 Findings

The themes resulting from the analysis were structured into two categories: 1) *motivations for including IoT in the computing curriculum* and 2) *choosing what IoT topics to teach and how*. The themes encompassed under *motivations* focused on the participants' perceptions of why IoT topics should be taught. The themes encompassed under *choosing what IoT topics to* *teach and how* focused on what skills, concepts and ways of thinking about technology might be appropriate to teach, and at a general level, how they might be taught. The findings suggest that when considering what to teach to schoolchildren about IoT, it is important to begin by considering what topics will provide a useful skill set for them to be able to engage with thinking critically about IoT technologies, and choose the concepts that enable this skill set. Moreover, the participants suggested that there are many opportunities to get schoolchildren started with exploring IoT, especially through exploring physical hardware and reflecting on personally meaningful data.

5.2.1 Motivations for incorporating IoT into the computing curriculum

The first category of themes identified relate to the participants' perceived motivations for incorporating IoT topics into the computing curriculum. These are: *1) providing a useful skill set for data literacy, 2) promoting realistic perceptions of new technologies, 3) promoting critical thinking about new technologies*, and *4) helping people build an understanding of novel types of interfaces and interaction paradigms*.

Motivation: Providing a useful skill set for data literacy

All of the participants referenced the importance of considering the *'utility'* and *'usefulness'* when considering the question of what to teach children about IoT. Drawing on her teaching experience in both higher education and at the secondary school level, *U2* articulated a distinction between the goals of specialized, post-secondary education and primary/secondary education. Specifically, she argued that where higher education should aim to provide a deep conceptual understanding of how technologies work, the goal of primary and secondary education should be to enable new ways of thinking about technology, and to drive an interest in further learning. The participants also discussed that IoT learning in schools should not necessarily endeavor to promote an algorithmic understanding of *"low-level concepts"* (*D2*), but rather a *"data literacy"* (*M1, M2*), which M1 described as having an *"awareness"* of and *"feeling comfortable"* with computational terms. *M1* further discussed how this type of basic awareness and comfort with computational terms could serve as a starting point for inspiring further interest in learning about computing, without making it seem intimidating.

Motivation: Promoting realistic perceptions and expectations of technologies

The participants also viewed a main motivation for including IoT topics in the computing curriculum as mitigating the current mismatch between the popular perception and the reality of IoT. *D1* argued that the *"problem with IoT is that the hype has arrived too soon almost."* Three of the participants discussed how images of IoT as presented by media and manufacturers are often overblown (*D1, D2, U1*). For example, *D1* said *"…it's all just coming in as smart cities are going to be this amazing thing […], going to solve all the problems, magically your car will navigate itself around and find a parking space […] and a lot of it is a whole lot of rubbish".*

D2 argued that in reality, *"the IoT is a mess"*, and that its core technical components are still in a state of flux—a problem that stretches to how it is defined and implemented in industry. In particular the 'Internet' component of IoT to date was seen as controversial. The participants discussed how the dominant view in the IoT industry today is that IoT technologies are still in an 'Intranet' state, and that most current IoT technologies are largely not openly connected in a way that would render them a true 'Internet of Things' (*D2, U1*). Additionally, commercial companies often market devices that are only locally wirelessly connected to other devices (e.g., through Bluetooth) as 'IoT technologies'. Furthermore, standards for data types are in a state of flux between manufacturers. Specifically, *D2* discussed the example of the differences in how a standard step is measured between wearable manufacturers: *"they actually put the FitBit Jawbone and a few other sensors on a person and they went for a walk and they gave wildly different results."*

The participants discussed how a lack of awareness of these issues by the general public might promote unrealistic expectations of IoT technologies (*D1, D2, M1, M2*), along with an acceptance of potentially misleading claims about their properties, capacity and capabilities (*D1, M1*). Therefore, based on the interviews, a main motivation for including basic IoT topics in the computing curriculum seems to be mitigating misconceptions about IoT, by providing people with an understanding of the technical basis of IoT, as well as the current limitations and issues with IoT technologies.

Motivation: Promoting critical thinking about new technologies

All six participants highlighted how IoT raises new societal questions around the privacy and security of personal information, which the public should be involved in answering. These are often highly contextual in nature rather than being tied to understanding how hardware and software work at a purely functional level. For example, *D2* discussed how, in answering the question of what constitutes sensitive data, it must be considered that data from the same type of sensor may be viewed as less or more sensitive, depending on factors related to the ecosystem in which it is embedded; these include, for example how often the data is transmitted, the context in which it is used, and other information with which it is associated. Similarly, M2 argued that *"[the public] don't often think of the flip side—like, oh my life will be so easy because everything will be automated. On the flip side, someone knows what you're doing all the time, where you are, how much you spend on milk…and how useful is all of that?"* The participants felt that educating people about IoT may provide them with the skills to question this: *"it's important to give people critical tools and not just buying stuff because someone said that's really good"* (*M1*).

D2, M1 and *U1* also discussed how encouraging critical thinking might enable the public to contribute to the future vision of IoT, and potentially shift power dynamics between manufacturers and the public. Currently, due to lack of critical engagement with the IoT: *"there's not really consumers going like whoa whoa whoa, I don't want that…so they're just given what they're given, they have to go…I buy it or I don't buy it and…that's a real problem"* (*D2*). This is important because it can be *"potentially dangerous in how that affects transfer of power"* (*M1*), and equipping the public with the tools to think about such issues may democratize future developments.

Motivation: Helping people build an understanding of novel types of interfaces and interaction paradigms

IoT technologies are part of a trend toward increasingly implicit and invisible interactions with technology. *M1* discussed that as technology becomes increasingly embedded in everyday objects, failing to see devices with novel interfaces as computers, or to understand how they work, becomes problematic. *M2* added that this is a particular problem with new IoT technologies where "*too many laypeople don't understand that they are generating data"*. Similarly, *D2* discussed in detail an *"extreme example"* of a coffee cup that invisibly senses and wirelessly transmits the level and temperature of the liquid it holds to a third party advertiser. He argues that this type of embedded and connected computing brings a new onus on the user to understand how computational devices function. With no prior understanding of IoT technologies, this is difficult especially where *"[the device] doesn't look like a computer, it doesn't have a read out on it, it might have some symbol like the NFC thing or the WiFi thing…but you don't really know what it's doing or when it's doing stuff"* (*D2*). Within this scope, the analysis of the interviews indicated that introducing people to technologies that break the stereotypes of traditional computing interfaces is a key motivation of teaching IoT.

5.2.2 Choosing what to teach and how

The second category of themes identified were about what types of IoT topics might be selected to teach IoT, and how learning activities might be designed to convey them to children, especially those aged 8 to 12. To this end, the participants made a number of suggestions, including: 1) *balancing low-level and high-level topics*, 2) *enabling higher level thinking by using personally meaningful data* and 3) *providing concrete opportunities for exploration of abstract ideas*.

Choosing what to teach and how: Balancing low-level and high-level topics

A question included in the interviews was how to choose the appropriate level of abstraction for topics to be included in an IoT curriculum. IoT topics, for example how an IoT system works, might be taught at a number of levels of abstraction: at the level of its general functionality and potential real-world applications; at the level of understanding how data within the system is collected and transmitted; or at the lowest level, by learning about, for example, underlying networking protocols (*U2*). Even the participants who teach IoT at university level (*U1* and *U2*) underlined that when considering IoT education for schoolchildren there is a need to abstract away from concepts that cannot be readily connected to real world applications. For example, *U2*, who as part of her IoT course teaches university students how processors read and write bits to/from peripheral devices, discussed how she considered these types of concepts to have little relevance to schoolchildren just starting to explore IoT.

When discussing this issue, D2 and U2 reiterated that their perceived motivation for teaching computing was as *providing a useful skill set*. They both explicitly argued against teaching children, to begin with, about the low-level mechanics of IoT topics, which *D2* enumerated through examples such as understanding networking protocols and the mechanics of client/server programming. The reason for this is that they assumed it would be too difficult and not useful for children just starting out learning computing. However, across all of the participants' responses, there was a general agreement that a basic understanding of how electronic components work and some procedural knowledge of IoT topics is important; this was illustrated by *M1* and *M2* with the example that children should understand *how* wirelessly connected devices gather and send data, without necessarily being able to explain how this happens at the lowest level.

When discussing this topic, D2 used the example of the *Creative Commons* framework ["Creative Commons," n.d.] as an analogy to finding the appropriate level of abstraction for teaching children about IoT. Within the Creative Commons license, *"there's 3 stages—there's the logo, there's the more human readable stuff and then there's the lawyer and machine readable stuff…and you should be able to see the logo, understand what this means to* *you"*, without necessarily being able to understand the intricacies of the low-level functions.

Choosing what to teach and how: Enabling higher-level thinking by incorporating personally meaningful data

D1 and *M1*, who had extensive experience in planning and running workshops to teach the public about a variety of technologies, discussed how in their experience, planning interactive sessions that capitalize on personally relevant content, can lead the participants to have more engaging experiences and insightful discussions. *M1* for example describes an informal IoT learning workshop he planned for adults, where he created an activity for people to *"sit down and make things based on tidal data [from their geographical area]. It's kind of a space for them to talk about where they're from, what their relationship to [the data] is."* In particular, he discussed the benefits of using hands-on, and personally relevant activities to promote the development of critical thinking about technology: *"if you just sit [people] down and say, what do you think about privacy on the internet, people go 'oooh, what do I think of?' […] it's quite interesting as soon as you set people a task or an activity, they reveal stuff about themselves in a completely different way"* (*M1*).

Choosing what to teach and how: Providing concrete opportunities for exploration of abstract ideas

Another theme identified was that 'hands-on' experimentation with IoT technologies can provide a way for children to easily explore abstract ideas in a tangible and personal way. Specifically, several participants advocated for experiential learning through tinkering and making with physical computing toolkits. *D1, M1* and *U2* referenced their experiences with using physical hardware components as a way to instigate both conceptual understanding and critical thinking when teaching about computing in general. They discussed in particular how understanding topics like the unreliability and the malfunction of hardware in the IoT might be constructed through physical computing experiences (*D1, M1, U2*). *D1* noted the powerful learning experience that might arise from tinkering with a sensor and realizing that *"the wire's not plugged in quite right and you get really weird results, or everything seems to be ok, you can get weird results."* Using an example of a person seeing an inaccurate advertisement about an IoT technology, he suggested that this kind of learning experience *"gives you the skills go…excuse me, I've covered some data and I know that's not the case"* (*D1*). *D1* and *M2* also provided examples of how planning lessons around hands-on exploration of the limited storage capacity of microcontrollers could be used to teach children that data storage is not limitless, but rather constrained by physical factors. Additionally, *M2* and *D2* discussed how including hands-on exploration with IoT components in the curriculum could serve well as a starting point for learning about more complex computing concepts and trends, like machine learning and big data. The participants reflected that the physicality of IoT devices might make fundamental computing topics such as what data is, and how it is gathered by hardware components clear, which could ultimately serve as a starting point to learning about more advanced computing topics.

5.3 Discussion

All of the participants perceived a main reason for teaching IoT to schoolchildren to be providing a *'useful skillset'* for thinking about and using IoT technologies. The participants highlighted that a useful skillset should include: understanding the reality and limitations of current IoT technologies; understanding how new types of interfaces collect and transfer data; and thinking critically about the usefulness and societal implications of IoT systems. In order to support these learning outcomes, it is clear that there is a need to consider how to teach for both *conceptual understanding* and *higher-level thinking* about IoT. Engaging in *higher-level thinking* can be defined as being able to not only understand how a technology works, but also to able to analyze, evaluate and create technologies. *Conceptual understanding*, in contrast, relates to declarative knowledge, for example understanding how a sensor works and what sensor reliability is, as well as understanding how data is represented (e.g., how a step is measured).

A question that led to some consideration amongst the interviewees was what to teach at the conceptual understanding level, and conversely, how to decide what to abstract away from. Based on their discussions, IoT topics chosen for primary and secondary curricula should promote a level of understanding that addresses how the fundamentals of IoT devices work, and is useful to apply in real life contexts, but abstracts away from expert-level conceptual knowledge (e.g., network protocols, gateways, client/server programming). It seems that the choice of what to include at the conceptual understanding level should be made on a case-by-case basis, by starting from first thinking about how a particular topic can support higher-level thinking about IoT, and then working out what is *useful* for children to understand about it. For example, when considering teaching children to reflect on the implications of using an IoT fitness tracker, it may be useful to teach about how the tracker works, and how to determine its reliability and accuracy, but not about the way the sensor circuit is designed (e.g., how operational amplifiers amplify the signal).

Based on the findings from the interviews, the following topics are suggested as being appropriate for starting to teach children at the end of primary school (i.e. 8-12 year olds) about IoT:

- Learning about the capabilities and limitations of **IoT hardware** (e.g., sensors, actuators, microcontrollers), in order to be able to challenge misleading claims.
- Learning about what **data** is and how it can be represented, as well as thinking about the meaning of different representations of data (e.g., how a step can be defined and measured).
- Learning about how **IoT systems** work and how they are implemented; for example, understanding that a device is generating data, understanding where the data is transferred and thinking about how individual devices in the system contribute to the system as a whole.
- Learning about what **privacy and security** are, and thinking critically about the significance of these terms in different data contexts (e.g., personal health data, data about the home, warehouse inventory data).

Each of these topics encompasses an element of both conceptual understanding and of higher-level thinking. Based on the participants' discussions and suggestions, a table was created to clarify the goals and content to consider when beginning to design IoT activities for children. This is summarized in Table 5.2.

A larger diversity of IoT topics could have be defined – for example, learning about how edge and cloud computing work and about large datasets from aggregated IoT devices. However the four introductory topics described here are suggested as a way of providing children with the tools to begin understanding and thinking critically about

Table 5.2: Suggestions of four IoT topics that may be appropriate to introduce to children. The topics are broken down into conceptual understanding outcomes and higher-level thinking outcomes.

Topic	Conceptual Understanding Outcomes	Higher-level Thinking Outcomes
Hardware	What are microcontrollers, sensors and actuators? How do they work? Are they accurate/reliable? How do they work together to create an IoT device?	What are the limitations of IoT hardware? What happens if a piece of hardware is inaccurate or unreliable?
Data	What is data? How can data be represented? How is data physically stored?	Are some types of data representations better or more informative than others? What is the value in storing this data? Does this vary depending on the context?
Systems	How do individual IoT devices connect to others/to a larger system? How is data transferred within an IoT system?	What is the relationship between the individual device and the system of which it is a part? What is the value in this device working as part of a bigger system?
Privacy	What is privacy? What are the principles of designing privacy into an IoT system?	To what extent does privacy matter for this IoT system? What do different data representations (e.g., real time, aggregated) mean for the privacy of this system?

IoT, and as a way of driving their interest in further learning without being intimidating.

A question that emerges from this scoping of what topics to teach as part of IoT for schoolchildren is how the components relate in practice. Specifically, what remains to be determined is how best to design *learning activities* that promote the development of both conceptual understanding and higher-level thinking about IoT. Something that the participants discussed was the importance of engaging children in hands-on experimentation with IoT hardware. This seems like a promising approach, rather than teaching them about abstract concepts first, such as networks or data flow models. However, what is unclear is how introducing them to the 'nuts and bolts' of IoT by experimenting with hardware (e.g., sensors and representations of data collected) can promote conceptual understanding and higher-level thinking of how an IoT device works. Where does the connection happen? Can this type of hands-on activity enable children to deduce an abstraction from specific examples and begin generalizing to other settings? Furthermore, at a theoretical level, what is it about beginning with a hands-on learning activity that can lead a child to higher-level thinking?

The goal of the remainder of this thesis was to explore in depth, at a theoretical and practical level, how to enable children to move from taking part in a concrete physical activity to being able to reflect on the conceptual learning outcomes and engage in higher-level thinking. In particular, a focus was to determine how capitalizing on interaction through the body, collaborative learning and engagement with personally meaningful data could enable children to make these connections. To theorize how this might occur, constructivist and constructionist theories are drawn upon (discussed in Chapter 2). Specifically, the research took a constructionist and social constructivist stance where the design of the learning activities: 1) used a physical computing toolkit as an object-to-think-with [Papert, 1980], and 2) aimed to encourage dialogue between peers, as a way of helping children to reflect on what was being learned [Dillenbourg, 1999; Vygotsky, 1978].

5.4 Summary

This chapter has summarized the findings from a set of interviews from a range of IoT professionals who talked about which IoT topics might be incorporated into a computing curriculum for children aged 8-12 years old. There was much overlap in their answers suggesting that there is agreement about what to teach and how to teach. Two core aspects that were identified which will be explored in depth here, were higher-level thinking and conceptual understanding. To start, it was suggested to provide children with hands-on learning experiences using a physical computing hardware.

However, how best to teach the topics using physical computing that will enable children to move from hands on activities to conceptual understanding and higher level thinking about IoT remains an open question. The remainder of the thesis was framed to address this, including considering what kinds of hands-on learning activities can promote reflection. Moreover, how can higher-level thinking about aspects of IoT be promoted for children just starting to learn about computing? The next phase of the research involved determining how to design and evaluate introductory learning activities about IoT.

CHAPTER 6: INITIAL EXPLORATION OF USING PHYSICAL COMPUTING TO TEACH IOT

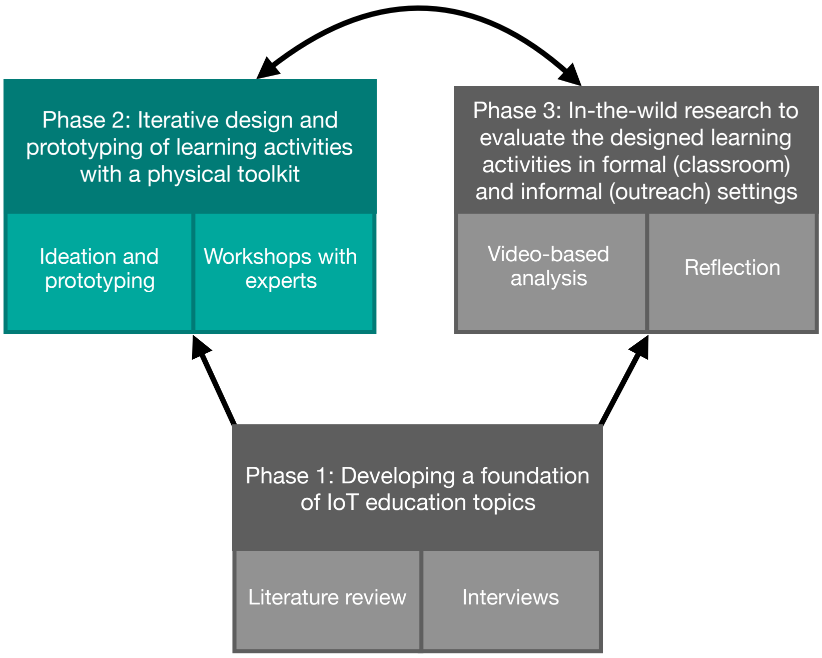


Figure 6.1: This chapter addresses the initial stages of ideation and prototyping with the Magic Cubes, as well as a workshop with experts.

The findings from the interviews with IoT experts revealed potential IoT topics that were considered suitable for teaching to schoolchildren. The next stage of the research involved investigating how these might be taught. It was decided to design learning activities that capitalize on the use of a physical computing toolkit. One of the main reasons was because physical computing toolkits can map onto constructivist, discovery-based learning – which is the pedagogical approach adopted for this thesis. In particular, they can promote physical, sensory experiences, which can enable novices to learn computing concepts that are otherwise inaccessible (e.g., [Johnson, Shum, Rogers, & Marquardt, 2016; Zuckerman, Arida, & Resnick, 2005]). For this purpose, the Magic Cubes toolkit, developed at the UCL Interaction Centre, was chosen. One of the benefits of the Magic Cubes is their flexibility in terms of how they can be used in a learning context. In particular, they can support a variety of task types when learning about computing; they can be used both for learning to code, making and discovery-based tasks.

To design learning activities using the Magic Cubes entailed first examining the toolkit, and explicating which features could be used to teach IoT topics. Following this stage, rapid ideation and prototyping were carried out to develop potential introductory, discovery-based activities with the Magic Cubes. The topic chosen for this was systems thinking – as understanding how IoT systems are connected and how parts in an IoT system interact was considered of central importance to IoT from what was said in the interviews. Systems thinking relates to the ability to understand the interactions between parts in a complex system, as well as the emergent behaviors resulting from these interactions [Richmond & Peterson, 2001]. Basic systems thinking skills include understanding reciprocal causality, as well as how interactions between parts can lead to non-linear causal patterns, for example through feedback loops [*ibid.*]. These concepts are seen to relate directly to the IoT, as interactions between wirelessly connected parts can have profound effects on the behavior of the system as a whole.

To begin, two activities related to systems thinking were designed. These were evaluated at a workshop held at the BBC, where a team of producers and researchers working in children and learning had been invited to take part. They provided feedback on the use of the cubes and the proposed activities, together with making suggestions about the design of future activities for other introductory IoT topics. Their main feedback was how to design the discovery-based activities to be more introductory and how to make it more obvious as to what the user input and output are. Based on aspects of their feedback, new learning activities were designed and tested.

This chapter describes the Magic Cubes in terms of their functionality and affordances, and the design process that was followed when designing initial learning activities with the Magic Cubes. Next, it presents the findings and discussion from the initial exploration of the Magic Cubes to teach systems thinking concepts. The outcome from this stage of the research was to devise a set of design strategies intended to help inform discovery-based learning activities that can be used to teach IoT. These informed the set of subsequent studies conducted throughout this thesis.

6.1 Context and Motivation for Using the Magic Cubes

The Magic Cubes toolkit was created at the UCL Interaction Centre [Marquardt, Lechelt, Rogers, & Shum, n.d.] as part of a broader research agenda of innovating new platforms to teach about computing, and specifically, to lower the entry threshold to learning about physical computing and IoT. Its design was inspired by two earlier physical toolkits that were also designed at UCL: the Engduino and the MakeMe, which I describe next before presenting the Magic Cubes.

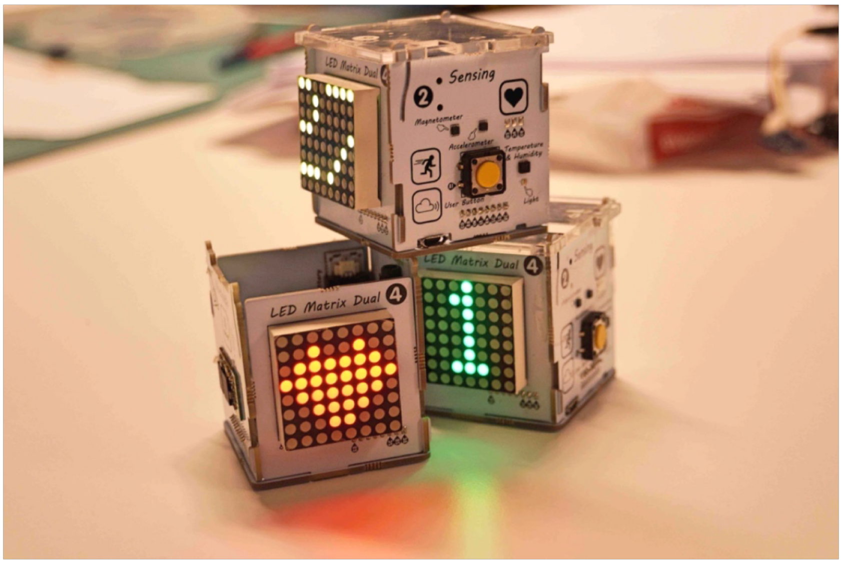


Figure 6.2: The Magic Cubes toolkit.

6.1.1 Engduino

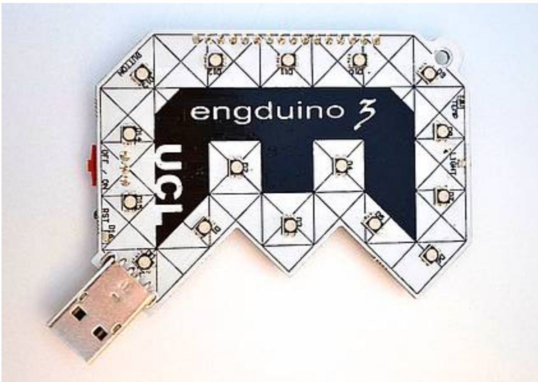


Figure 6.3: The Engduino toolkit.

Engduino was originally developed for use at UCL outreach workshops to teach schoolchildren about computer science and coding. It is an Arduino-based toolkit embedded with a variety of sensors, including an accelerometer, a temperature sensor, as well as a button, 16 neopixel LEDs and infrared communication. The Engduino was designed as an all-in-one toolkit that does not require building a circuit to get started when programming with physical components. Instead, the input and output components are embedded in the toolkit alongside the board. The Engduino was primarily aimed at children in Key Stage 3 (11-14 years old), but also designed to be inclusive for wide audiences ["Engduino," n.d.]. Informal testing of the Engduino by researchers at UCL through workshops with a diversity of audiences showed that the Engduino inspired much creativity when learning to code with physical computing. This included children learning to code through making spelling games, designing their own emoticons, and recording data about themselves, like their own heart rate. One of the benefits of a physical device with a variety of components already embedded is that it made it easier to get started and enable children to turn their ideas into working prototypes using the Arduino programming environment – which uses a simplification of the C/C++ programming languages ["Arduino," n.d.]. However, the researchers involved reflected that learning to turn their ideas into code in Arduino proved to be challenging for children who were beginners to programming. To enable them to progress with their ideas, the children required much guidance and instruction from the teachers and researchers.

6.1.2 MakeMe

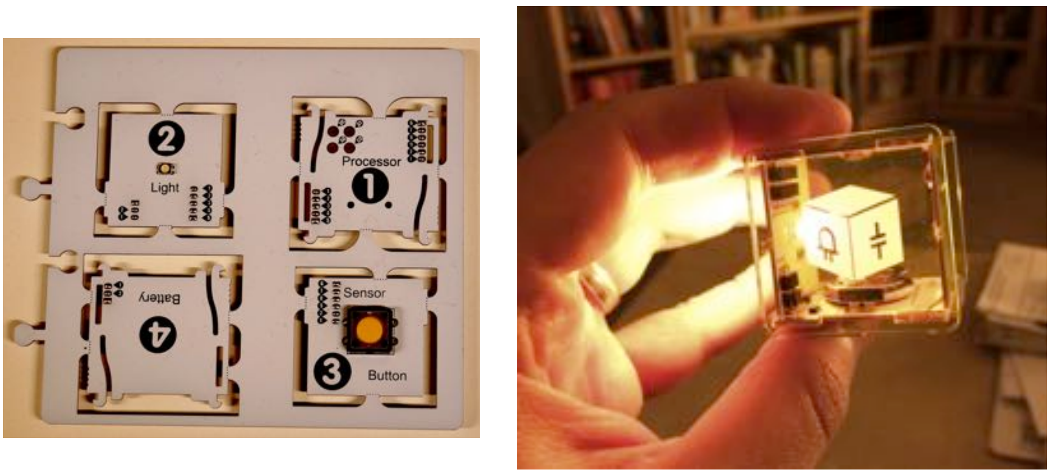


Figure 6.4: (left) The MakeMe printed circuit board before being assembled, (right) the assembled MakeMe cube with a glowing neopixel light.

The MakeMe cube (see Figure 6.4) was inspired by the physicality and flexibility afforded by Engduino. In collaboration with the BBC, the UCL Interaction Centre tried to make a simpler toolkit that could be constructed and explored without the need to do any programming. The design concept was a device that could enable children of all ages to make a cube with sensor input and a digital output that would do different things depending on the mappings between them. Another requirement was for it to be appealing to anyone. The format of a cube was selected as it was considered a gender-neutral device for exploring computing concepts [Rogers et al., 2017]. The UCL team worked closely with a professional designer and a member of the BBC learning team for several months to develop the components of the cube and to work out how best to fit them all together.

The toolkit comprises a custom-built flat printed circuit board with four sides that can be assembled into a cube. The four sides house: the processor, input (an accelerometer and a power button), output (a single neopixel LED) and power (a slot with a battery in it). The four component sides were designed to appear as a flat pack (Figure 6.4, left). The idea was that each child would be given one and be able to see it as a construction kit that they need to make into a cube (see Figure 6.4, right). Each component was designed to be popped out of the casing at the edges. To complete the cube two further clear acrylic sides were provided. Once assembled, the cube starts to function; when shaken at different speeds, the processor maps the speed of movement (as sensed by the accelerometer) to different colors shown via the neopixel light inside the cube.

The key idea behind the MakeMe is that beginning to learn about physical computing hardware by initially having to assemble the sides together into a functional circuit, would enable children to understand how electronic components function in relation to how a sensor maps onto output. Johnson et al. [2016] evaluated the MakeMe in terms of how the act of constructing the cube, as well as learning about the functionality of its components through discovery-based tasks like shaking and gesturing, supported the learning process. The findings from their study showed how the act of physically constructing and experimenting with the MakeMe fostered much curiosity about the electronics that comprised the cube. Moreover, the act of constructing the cube led young children (ages 6-8) to perform better in a post-test which assessed their conceptual understanding of the cube's electronics, compared with children who were given a ready-made cube. They concluded that the act of constructing was a powerful way of introducing children to the functionality of physical hardware [*ibid.*].

While successful in terms of supporting initial learning about sensors and their effects, the MakeMe cube is limited in scope in terms of what it can be used to explore. The idea was that it would be affordable to be given away free to get children curious. Next, a more extensive prototype – called the Magic Cubes – was designed using the same principles behind the design of the MakeMe. However, the Magic Cubes incorporate a larger variety of electronic components with the aim of supporting learning more about IoT, through enabling a wider variety of discovery-based learning, as well as coding.

6.2 The Magic Cubes

The Magic Cubes were designed as a flat pack sheet of five sides to be constructed, similarly to the MakeMe, but with a wider range of electronics with which to tinker, experiment and program. Each of the five pop-out sides corresponds to a core component of a computer: the processor, input, output, power and connectivity (see Figure 6.5). The design rationale is that the sides can be assembled easily into a hand-sized cube. Whereas the MakeMe cube measures $4cm^3$, the Magic Cubes are slightly bigger, measuring $6cm^{3.}$

Figure 6.2 shows three Magic Cubes that have been constructed. The top one shows how clear acrylic is placed on one side of the cube that allows users to peek into the cube's internal circuit to see the embedded electronic components. The Magic Cubes have more sensors embedded in them than the MakeMe, that can detect temperature, light, magnetic fields and acceleration. Additionally, the Magic Cubes have a headphone jack port, into which other types of sensors (e.g., a pulse sensor) can be plugged, to extend the functionality of the toolkit. The data collected from the sensors can be coded to appear as a visualization (e.g. an animation) through the embedded 8x8 pixel LED matrix or to control the internal multicolor neopixel light. The Bluetooth component enables the cubes to be connected to each other, or to other devices such as mobile phones or tablets. The components of each side of the cube are numbered and described in more detail in Figure 6.5.

The Magic Cubes were designed as a general-purpose building block. Like the MakeMe cube, they were intended to appeal to computing novices, and their form factor was designed to be intriguing and playful, as well as to encourage collaboration and

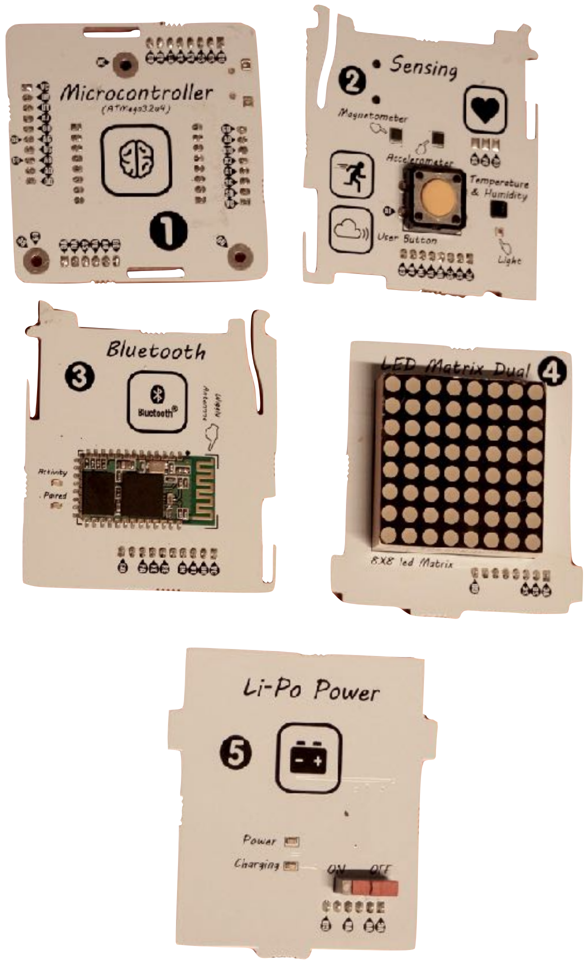


Figure 6.5: The five sides of a Magic Cube.

(1) top-left: a **micro-controller** side with an embedded ATMEGA32U4 processor.
(2) top right: a **sensing** side including the following sensors: Light sensor, temperature and humidity sensor, 3-axis accelerometer, magnetometer and button, and a headphone jack that can be connected to other sensors, like a pulse rate sensor or a galvanic skin response sensor.
(3) middle left: a **wireless connectivity** side with an HC-05 Bluetooth module, which can be used to connect to other cubes or other Bluetooth-enabled devices such as smartphones.
(4) middle right: An **output** side consisting of an 8x8 red and green LED matrix.
(5) bottom: A **power** side including a rechargeable Lithium polymer battery for wireless use.

creativity while learning. Because the cubes were created with embedded sensors and actuators, they enable the users to explore how the components work together straight away without having to worry about connecting input and output components with a circuit. Hence, the emphasis is on exploring or creating something using the cube from the start rather than having to wire a circuit up first to make it work.

Once assembled, the input and output functionality of the cube can be programmed by users, using either text-based or drag-and-drop visual versions of the Arduino programming language [“Ardublock,” n.d.; "Arduino," n.d.] (see Figure 6.6).

Alternatively, the cube can be explored through discovery-based activities. By this is meant where an instructor uploads code onto the cubes to make the embedded components function in a specific way, and the learner explores the cubes to figure out what the uploaded program does. This flexibility of use has the potential to appeal to novice users. This flexibility also contrasts with the Engduino, which mainly supports programming with data, and the MakeMe, which only supports making and limited discovery-based learning. Figure 6.7 summarizes the four uses for the Magic Cubes, and how they relate to the IoT topics discussed in Chapter 4.

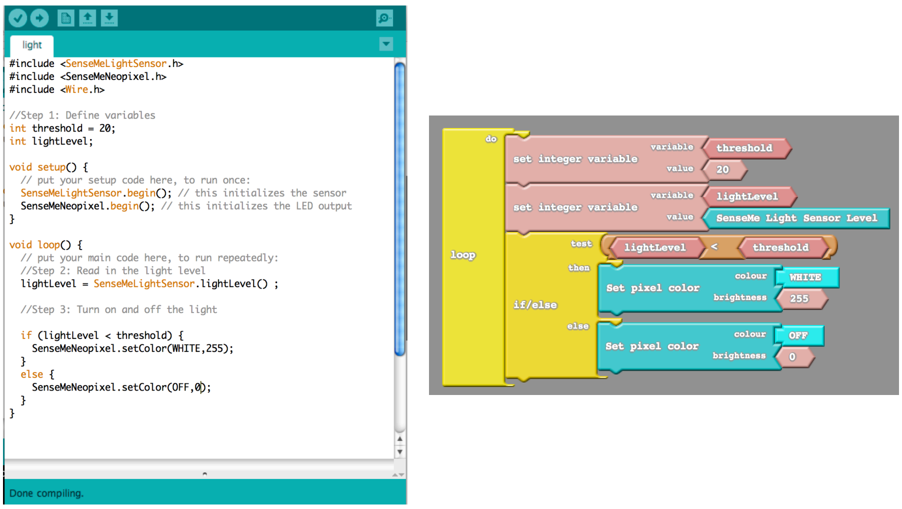


Figure 6.6: Two ways of programming the Magic Cubes, using (left) the Arduino programming environment and (right) the Ardublock drag-and-drop visual programming environment.

6.3 Initial Designs for Discovery Learning using the Magic Cubes

When I first joined the UCL Interaction Centre as a PhD student, the Magic Cubes had just been created and manufactured as a proof of concept, and had not yet been

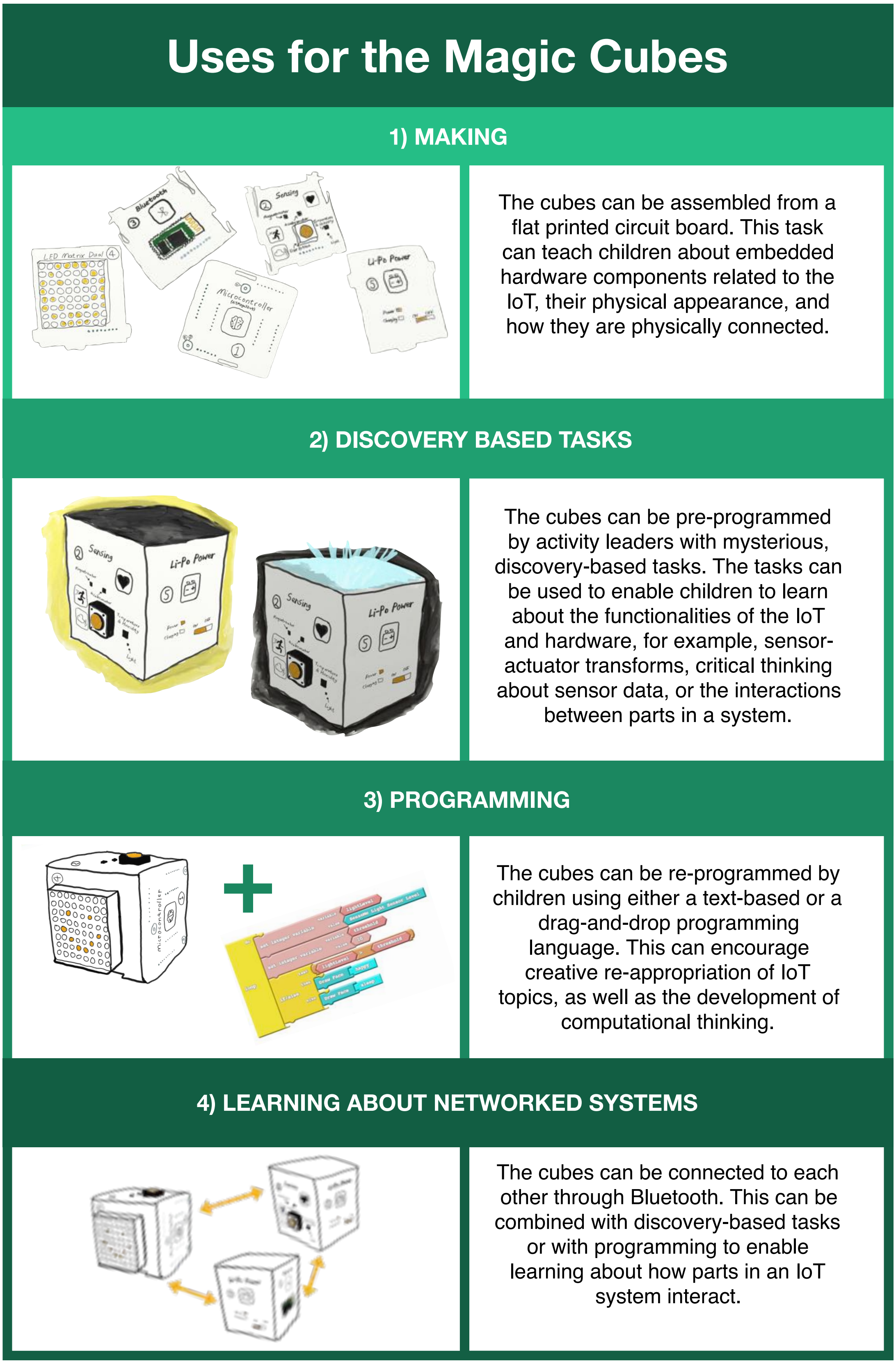


Figure 6.7: The four flexible uses of the Magic Cubes. These are: 1) making, 2) discovery based tasks, 3) programming and 4) learning about networked systems.

explored empirically. The challenge provided for me was to investigate how more advanced topics related to IoT could be taught using the Magic Cubes, beyond what has been done previously with the Engduino and MakeMe. Johnson et al.'s [2016] evaluation of the MakeMe demonstrated that there is much promise for utilizing a cube-shaped interface for discovery-based learning, especially in terms of promoting engagement and curiosity during the learning process. Because of this, I chose to explore how discovery-based learning might be capitalized on to teach more complex topics. To help design specific learning activities for this purpose, I used ideation and prototyping to explore how to capitalize on the affordances and constraints of the Magic Cubes. Next, I describe the initial design process followed for ideation and prototyping discovery-based tasks with the Magic Cubes.

6.3.1 Designing discovery-based learning activities to teach about systems thinking concepts

As a first step, it was decided to consider how children could use the cubes to simultaneously explore several IoT concepts: namely, the functionality of sensors, actuators, and wireless connectivity. Additionally, at a more abstract level, the aim was to investigate how to convey systems thinking concepts through the Magic Cubes—in terms of how the parts in a connected system of cubes a) co-operate together, and b) their interdependencies. This was because, based on the interviews in Chapter 4, understanding how individual IoT devices fit into larger IoT systems is considered key to learning about increasingly complex IoT topics – for example, thinking critically about how IoT systems work as a whole.

6.3.2 Ideation and prototyping

To begin with, I spent time exploring the capabilities and limitations of the Magic Cubes for conveying core concepts from systems thinking literature (see Table 6.1) for the core systems thinking concepts that were explored), and ideating, refining and implementing activities. The aim was to design specific activities that could show the relationship between the IoT devices and connected systems in order to help children understand 1) at a functional level, how sensors, actuators, and wireless connectivity work together to collect and transfer data in an IoT system, and 2) at an abstract level, why cooperation and interdependence between parts is necessary within a connected IoT system, and what happens when it breaks down.

Table 6.1: The core systems thinking concepts that were explored as part of the ideation phase. The * indicates that these concepts were used for the initial learning activities designed.

Concept	Description	Potential IoT Example
Reciprocal Interdependence*	A system in which all constituent parts are dependent on each other, and require each other in order to function separately	Two connected devices that require data from each other in order to be able to function.
Mutual Cooperation*	A system in which all constituent parts benefit from co-operative interaction, but in which co-operative interaction is *not required* for the constituent parts to function independently.	An IoT navigation system where the quality of the navigation data is improved by devices contributing their location, but the locations of individual devices are not necessary for basic functionality of the system
Pooled Interdependence	A system in which constituent parts do not directly interact, but collectively contribute to the functioning of the system as a whole.	Many individual energy sensing devices independently contributing to a system that estimates electrical grid usage over time
Emergence	The often unexpected, emerging behaviour of a system that is attributed to the *interactions* between its parts, rather than the behaviour of individual parts themselves.	It is difficult to predict what emergent behaviours might arise from future IoT systems. An existing example of emergence in technology is the emergence of new communities on social media.

I drew inspiration for the systems thinking activities from both systems thinking literature and real-world systems. Real-world systems include, for example, symbiotic systems in nature, interdependent systems in the human body, organizational structures in business, and social systems. In the ideation phase, I sketched different types of systems found in the real world, together with ideas of how they could be mapped onto the Magic Cubes (see Figure 6.8). The sketches focused on the ways in which core systems thinking concepts could be represented through discovery-based activities with two or more Bluetooth-connected Magic Cubes.

Figure 6.8: Examples of sketches representing brainstormed systems thinking activities, based on real world systems.

6.3.3 Initial design considerations for introductory activities

It was considered important that that the systems thinking concepts chosen for the introductory activities have low conceptual complexity, that is, not be hard for children without systems thinking experience to comprehend. It was also important that the interactions between the connected cubes be easy to discover. This was so as to show that the toolkit was not complicated, and to encourage further interest in using it for discovering and learning more. For these reasons, two systems thinking concepts were judged to be most appropriate for the introductory activities: *mutual cooperation*, and *reciprocal interdependence*.

Mutual cooperation refers to a relationship within a system in which all constituent parts benefit from co-operative interaction, but in which co-operative interaction is *not required* for the constituent parts to function independently. Reciprocal interdependence, in turn, occurs where both/all parts in a system are dependent on each other, requiring each other in order to function separately. These concepts were selected as they were less conceptually complex than other related systems thinking concepts, such as emergence or pooled interdependence (see Table 6.1). The challenge was to work out how to map the concepts of mutual cooperation and reciprocal interdependence to the Magic Cubes. It was decided to propose using only two interconnected cubes, rather than a larger interconnected system of cubes, which would have added complexity to the discovery task.

Through an iterative design process, informed by informal feedback from two HCI experts at UCL, two learning activities were designed to convey the concepts of mutual cooperation and reciprocal interdependence. The experts suggested that the activities should be abstract in nature, and not based on a specific natural or social system, hypothesizing that this might lead children to focus only on the system itself, rather than on reflecting on abstract, domain-general concepts. They also provided suggestions for making the interactions between cubes clear and salient, in particular suggesting concrete ways in which immediate feedback on user input could be displayed. The final learning activities that were developed and implemented by programming the Magic Cubes in Arduino are described below.

6.3.4 Activity 1: Mutual Cooperation

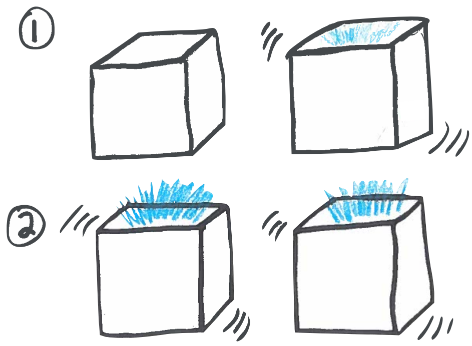


Figure 6.9: The Mutual Cooperation activity. 1) Shaking one cube produces a dim light in the cube being shaken. 2) Shaking both cubes at once produces a bright light in both cubes.

For the first activity (see Figure 6.9), the goal was to enable learners to explore what they can do with one cube alone and then compare this with what happens when two Magic Cubes are connected to each other using Bluetooth. The learners can see a difference when shaking one cube versus both cubes simultaneously; the lights embedded in the linked cubes shaken at the same time shine more brightly than compared with shaking one cube by itself. The metaphor of seeing a brighter light following the joint action of shaking two cubes simultaneously was intended to convey the idea of mutual cooperation, that is, that a system can do more when its constituent parts work together (in this case the lights shine more brightly).

6.3.5 Activity 2: Wheel of Interdependence

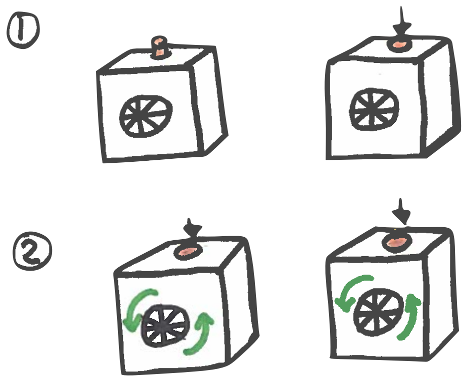


Figure 6.10: The Wheel of Interdependence Activity. 1) Pushing the button on one cube does not change the animation on either cube. 2) Pushing the button on both cubes simultaneously makes the wheel animation on both cubes 'spin'.

For the second activity (see Figure 6.10), the goal was to enable users to learn about the system concept of reciprocal interdependence by comparing what happens when interacting with two connected cubes, but this time with a different action. The learners are required to press a button on each of two Bluetooth-connected Magic Cubes simultaneously or alternately. When pressed together at the same time, the effect is to cause an animated wheel to spin for a set amount of time on the LED matrices of both cubes. If the learners then repeatedly press the buttons rapidly at the same time this causes the wheels to spin faster. When a button is pressed only on one cube, neither of the animated wheels is activated. This metaphor of making two spinning wheels appear through a joint action was intended to convey the idea of systems that only work when all of their constituent parts are active.

6.4 Workshop on Introductory Tasks with the Magic Cubes

A workshop was held with a team of children and learning experts at the BBC in order to obtain feedback about the efficacy of the discovery-based *mutual cooperation* and *wheel* *of interdependence* activities in conveying the intended systems thinking concepts. The participants were also asked to evaluate the learning materials that had been developed, that were planned to be used with the Magic Cubes. Following this evaluation task, they were asked to ideate other potential designs that could be used to promote discovery-based learning with the Magic Cubes. The reason for providing some initial designs for the learning activities was to demonstrate to the participants what was possible and how the two basic system concepts might be envisioned as introductory discovery learning activities.

6.4.1 Participants

Eight researchers from the BBC research and development team participated in the workshop to test the two potential IoT learning activities designed for the Magic Cubes toolkit. The participants were invited to take part based on their experience with creating innovative learning experiences for children. They understood that the research was part of a PhD partially funded by the BBC and so no compensation was provided for their efforts.

6.4.2 Materials

Instructions. Instructions were prepared on a sheet of paper for how to carry out the two activities using the Magic Cubes - with a view to how they would be used in a classroom or other setting. An important consideration of the approach adopted here is to consider how learning activities are to be used in the real world, taking into account the role of the instructor, the design of the instruction materials and the plan for each set of activities. For the *mutual cooperation* activity, the sheet included the following guiding instructions:

- Get together with your partner, and shake one of your cubes at a time.
- What is happening?
- Now, collaborate with your partner and shake both of your cubes at the same time.
- Did anything change in either or both of the cubes?

The sheet also included the questions that were intended to trigger reflection about the activity and its implications. For example, for the mutual cooperation activity, the following questions were included:

- How did the two cubes change when they were shaken together?
- Can you think of any examples in the real world where the action of one thing can influence another?
- How about any examples where one thing can make another stronger?
- How else do you think the cubes could collaborate together?

Appendix A includes all the instructions and questions provided.

Assessment method

For this initial set of activities, it was decided to use a traditional measuring instrument to determine what had been learned. To this end, a pre- and post- test were constructed. These included free-form questions, including:

- What is interdependence?
- What does cooperation mean?
- What are some examples of cooperation in the real world?

The pre- and post-tests also asked the participants to match different types of interdependence to their corresponding schematic diagrams—specifically, sequential, reciprocal and pooled interdependence (see Appendix A for all of the pre- and post-test questions).

6.4.3 Procedure

The workshop took place at the participants' place of work during a morning. It was split into two sessions, such that four participants, working as two pairs, took part in each workshop session. Each pair was given the instruction sheet and the two Bluetooth-connected Magic Cubes, and asked to work out how the sensors and output devices of the cubes were communicating together. In order to assess whether the concepts could be understood through the suggested activities, the participants were subsequently asked to verbalize what the cubes did for each activity, and what concepts the participants thought the activities were trying to convey (i.e., the target learning outcomes). The participants were also provided with the pre- and post- tests and asked how appropriate they were and if at the right level. After the participants completed the activities, an ideation session was held in order for the participants to provide further feedback on the Magic Cubes, the activities, and to make suggestions for future activity designs. Notes were also taken throughout the session.

6.4.4 Findings

Activity 1: Mutual Cooperation

The mutual cooperation activity was successful in conveying its target learning outcomes and inspiring discussion about cooperation among the participants. One problem that was identified, however, was that it was difficult to see the embedded light shine when shaking the cube, as it was hidden by the participant's hands. It was noted that it took several participants some time to notice the change in lighting effect when both cubes were shaken simultaneously. However, once the participants noticed the cause-effect between shaking and light both cubes at the same time versus just one, they found it easy to verbalize what the system was doing when prompted. At a technical level, when asked how the two cubes were interacting, all participants agreed that the cubes were able to send each other data, and that only when both cubes were being shaken did the light become brighter. The participants also used analogies from social and mechanical systems; for example, one participant mentioned that work may be made more efficient by two individuals collaborating together rather than one working individually.

Activity 2 : Wheel of Interdependence

In the wheel of interdependence activity, the participants took substantially longer to grasp what the cubes were doing and to work out the underlying systems rule being exhibited. Pressing the buttons simultaneously on both cubes proved to be non-intuitive, particularly as there was no feedback when the button on only one cube was pressed. However, similar to activity 1, once the mapping was discovered by at least one pair, all participants were quick to verbalize how the underlying system worked when prompted to explain this. The participants also realized that this activity represented a different concept than the first, that is, the necessity of all parts in a system to be functioning in order for the two animated wheels to work. When prompted, the participants provided analogies to the real world that were distinct from those they suggested in activity 1. For example, one participant provided the analogy of gear wheels—if one gear wheel is stuck, the other cannot move—it is only when both work together that the system can work.

General observations from the two activities

It was observed that the pairs of participants collaborated throughout the activities. This was evidenced in both activities by them spending considerable time instructing each other and reflecting on their discoveries when trying to work out how the mappings and lighting effects functioned. In addition, the participants who were the first to figure out how the lighting effects worked were quick to explain this to the other participants, without explicitly being asked to do so. For example, when one of the participants figured out that the brighter light in the mutual cooperation activity was a result of shaking both cubes, he instructed his partner to shake his cube, and then to lay it down on the table without moving it. As his partner did so, the participant verbally explained how he believed the cubes were interacting, which in turn drew the attention of another pair, and helped them to replicate the effect. In this way, the highly visible effects in the discovery-based activities seemed to promote joint attention between participants in their pairs, which promoted their reflection about what the rule behind the lighting effects was.

The activities also proved to be engaging in terms of how focused and challenged the participants were throughout the workshop. All participants concentrated on the task at hand, and showed a sense of achievement when they worked out what was causing the different lighting effects. Even before they were asked to brainstorm ideas, the pairs expressed ideas both to each other and to the researcher of how else the wireless connectivity in the cubes could be used and what other types of activities could be designed. Additionally, it was observed that for both activities, several of the participants continued playing with the cubes even after they discovered the lighting effects, and continued to do so even during the subsequent ideation session.

These observations suggest that the engaging and collaborative nature of the Magic Cubes and proposed learning activities provided the participants with opportunities to reflect on the task at hand, which helped them recognize the more abstract conceptual basis of the activities. It was observed, however, that the participants largely ignored the written guidance provided to accomplish the tasks. Instead, they focused directly on manipulating the cubes without referring to any of the prompts on the instructional sheets. Several of the participants commented that having to complete the pre- and post- test was intimidating and it would be better for children to be able to start straight away interacting with the cubes. They also did not attempt to complete the pre- or post- tests themselves.

Suggestions

During the ideation phase of the workshop, the participants suggested several ideas for the design of discovery-based activities for learning about IoT topics. These included:

(i) Facilitating discovery of the cubes' properties and functionality

(ii) Encouraging creativity and freedom when exploring the cubes

(iii) Using analogies from familiar games when designing discovery activities

(iv) Rethinking how to present the instructions and way of assessing learning

These are described in more detail below together with the implications arising from them.

(i) Facilitating discovery of the cubes' properties and functionality

A core idea for facilitating discovery-based learning that was suggested[2] was to limit the number of hidden variables in the activity, and to ensure that task-relevant variables are made salient to learners. The lack of familiarity with the cubes meant that in the first activity, the participants were faced with many novel variables (e.g., sensor-actuator mappings within individual cubes) in addition to the *task-relevant* variables of system mappings between multiple cubes. A suggestion that all agreed on was to provide an introductory activity that allows learners to explore the sensors and actuators for an individual cube so as to familiarize them with the components and what they do, before introducing activities involving more complex concepts, like interdependencies between parts in a system.

The participants' difficulty in being able to discover the effect of pressing the button in the wheel of interdependence activity when feedback was not given, suggests that it is important to make the mapping between the input/output of each individual cube more salient, particularly in activities where multiple cubes contribute to the overall function of a system. One participant suggested this could be achieved by using a color scheme on the LED matrix, where a green display indicates that an action has been performed on this cube, yellow indicates that an action has been performed on both this and the other cubes, while red indicates that an action has been performed on other cubes only.

[2] For this initial workshop, only shorthand notes were taken and no other data collection took place. For this reason, it is not possible to identify which participant(s) made the suggestions described. However, it was observed that all of the participants actively engaged in the discussion and made suggestions.

(ii) Encouraging creativity and freedom when exploring the cubes

Although the two activities received positive feedback from the participants, they all suggested that the learning activities should include an element of creativity in how to accomplish it as a way of enabling children to consolidate the concepts learned. One participant suggested that on completion of the discovery-based activity children could be asked to make other mappings between sensors/outputs of the Magic Cubes as a way of exploring how to create their own IoT system. Building on this, another participant suggested an additional activity as a decoding game, where one learner changes the sensor/output mappings between the cubes, and the others must decipher what has changed in the system.

(iii) Appropriating analogies from familiar games

The participants discussed that a good way to teach abstract concepts, such as those in systems thinking, could be to provide children with some conceptual leverage, through capitalizing on well-known games. Rather than using abstract light displays that have no direct relevance to the real world one participant suggested framing the concept of interdependence within a well-known game to make it easier to grasp. One example that was suggested was an adaptation of the "Simon" memory game. This is an electronic game where a disk of 4 colored sections creates a series of sounds and lights that a user has to repeat. If the user succeeds, a new series begins with another sound and light added to the end. The sequence becomes progressively longer and more complex until the player gets one of the lights wrong in a sequence. In the Magic Cubes context, it was suggested that the same kind of game could be instantiated, where learners would be presented with an increasingly complex sequence of patterns on the LED matrix that they would have to repeat by tilting the cube in different directions. The game could use two or more Bluetooth-connected cubes such that two participants have to repeat a sequence together. A question this kind of grounding in a familiar game raises, is whether it would encourage reflection on the underlying abstract concept or whether the user would remain wedded to the rules of the game?

(iv) Rethinking instructions and testing

The participants emphasized that the written instructions and pre- and post- test may be intimidating for children. In particular, the pre- test was considered to be counterproductive, as it included concepts that would likely be novel to the learner (e.g., asking children to define interdependence before learning what interdependence is). During the discussion, it was suggested that time should be spent investigating alternative methods for measuring learning outcomes in this research. It was also suggested that verbally explaining the instructions was a better approach than having written instructions as children find it difficult to read and follow when presented with such an engaging physical artifact.

6.4.5 Discussion of the Workshop Findings

The findings and feedback from the workshop were largely positive. The participants' engagement with the cubes was high and their comments favorable about using discovery-based tasks to teach introductory systems and IoT concepts. However, they were less enthusiastic about using formal testing and providing instructions in a written form. Additionally, the observations of the participants interacting with the Magic Cubes demonstrated the importance of taking into account the spatial affordances of having a 6-sided mobile artifact that can be grasped, held, moved and seen into. Having the lighting effect occur inside the cube while it was being shaken, made it more difficult to see than if it were to appear on the outside of a cube. It is important to make the mappings between physical sensors and actuators that are to be used to represent an IoT concept, be discernable by the learners.

Providing appropriate conceptual scaffolding to new IoT topics

One of the comments made was that introducing two Magic Cubes simultaneously with a systems thinking concept was too much to start with. It was suggested that children should instead have the opportunity to first explore individual cubes, before moving onto exploring interactions between two or more cubes. The workshop participants discussed at length what a more appropriate introduction to the session might be, and suggested that it should begin by enabling learners to experiment with simple cause and effect mappings (e.g. exploring the effect of shaking on the light display in one cube) and then build on these over time (e.g. shaking two connected cubes to see what different effects were produced). This feedback raises two important research questions that are subsequently addressed throughout the thesis: *(i) What is the appropriate difficulty of a set discovery task when learning about the IoT, and (ii) how can IoT concepts be scaffolded over time, while enabling learners to step back and abstract away the underlying concept from the hands-on activity?*

Measuring the learning process

The participants' feedback that providing a test before discovery-based exploration may actually impede engagement with the task raised questions about what kinds of alternative ways could be used for measuring learning effects. One possibility is to perform detailed analyses of children's learning *process* during the task. This can provide a different lens for investigating whether or not a learning task is successful. In the next studies designed, therefore it was decided to focus on revealing *how* discovery takes place during the learning process rather than strictly its learning outcomes.

6.5 Appropriating the Participants' Suggestions and Testing New Learning Activities for IoT

Based on the feedback in the workshop, two new discovery-based activities were designed and informally tested in order to investigate how the design suggestions of the participants could be implemented. The aim of the testing was to determine how easy they were to understand, and how much reflection people engaged in while interacting with the activities. For this purpose, a simple creative activity and a collaborative game were devised. These were:

(i) Color Mixer activity

(ii) Simon Tilt game

6.5.1 Design of the Color Mixer activity and the Simon Tilt game

(i) Color Mixer activity

The Color Mixer activity was designed to be simple in order to put across how two cubes could communicate through Bluetooth, and to enable more freedom when interacting with them than the two previous tasks. It involved one or two users mixing colors by using the two cubes. The activity enables them to mix two colors by using the Magic Cubes as if they were pots of paint and "pouring" the color of each cube into the other (see Figure 6.11). For this activity, the cubes were reciprocally connected, in that each transferred data to the other. Pressing the user button on each individual cube changed the color of the neopixel light in that cube to be one of three primary colors, red, blue or green. The color that appeared in a cube could be then "poured"

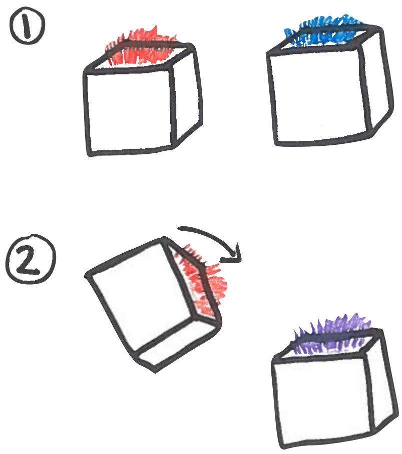


Figure 6.11: The Color Mixer activity. 1) The neopixel light embedded in the cubes is set to a different color in each of the two Bluetooth connected cubes. 2) Tilting one cube towards the other using a pouring motion mixes the color between the two cubes.

into the other cube, which was sensed using the accelerometer, with the effect of mixing the two colors. For example if the color in cube 1 was initially blue, and the color in cube 2 was initially red, "pouring" the red color into the blue colored cube would result in the color changing to purple in cube 2. Four HCI researchers tried this activity out. It was found to be easy and intuitive to follow and all were able to explain how it worked.

(ii) Simon Tilt game

The "Simon Tilt" game was designed around the basic rules underlying the Simon memory game that was mentioned earlier, namely asking users to repeat ever-longer sequences of arrows, by tilting a cube in certain directions, which were sensed using the accelerometer. The game is intended to be played by two players, each holding one cube. The goal is for the pairs to learn how to tilt their cubes to follow sequences of arrows that are displayed on the LED matrix of the cube.

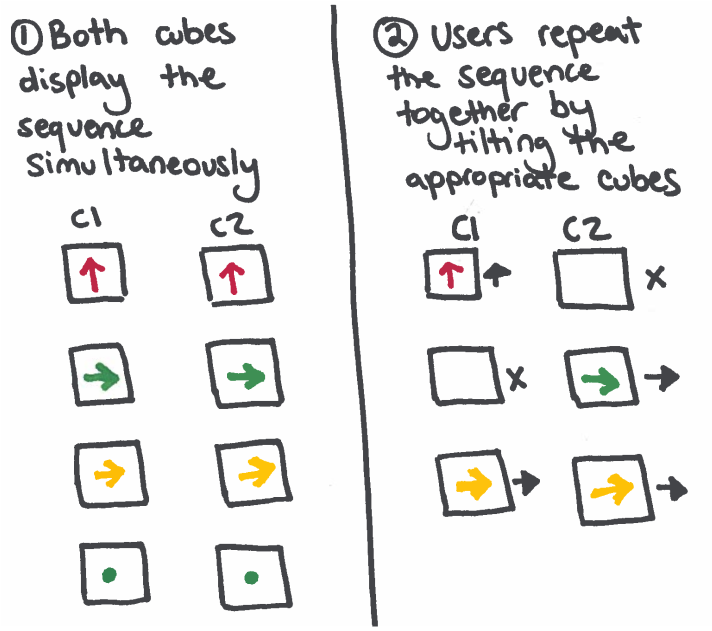


Figure 6.12: The Simon Tilt game. 1) Both cubes display a sequence of red, yellow and green arrows simultaneously. Once the sequence has finished a green dot is presented on both cubes. 2) The users repeat the sequence together by tilting the appropriate cubes. To repeat a red arrow, only cube 1 is tilted. To repeat a green arrow, cube 2 is tilted. To repeat a yellow arrow, both cubes are tilted simultaneously. In the sketch, the black arrows represent the direction in which the cube needs to be tilted. The black *x* signifies that the cube should not be tilted.

For this purpose, the two cubes were connected through Bluetooth so that they could communicate with each other. For each round of the game, the LED matrix on each cube simultaneously displayed a randomly generated sequence of green, red and yellow colored arrows, each of which pointed in one of four directions: North, South, West and East. For example, a simple sequence to follow is a red arrow, followed by a green arrow and then a yellow arrow. The color-coding of the arrows was chosen to make the mapping between the cubes salient. Specifically, the red arrows corresponded to needing to tilt cube 1, the green arrows corresponded to needing to tilt cube 2, and the yellow arrows corresponded for a pair of users needing to simultaneously tilt both their cubes. After the full sequence of arrows was displayed, a green dot was presented on both LED matrices to indicate that it was ready for user input in the form of tilting the sequence back. The players then need to collaboratively tilt the cubes in the appropriate directions in order to repeat the sequence (see Figure 6.12).

Informal testing of the first design iteration of the game with four HCI researchers at UCL revealed that the game was difficult to understand, in particular due to the lack of clear instructions on the interface. Specifically, people found it difficult to know when the sequence ended, and tilted the cube in the direction of the arrows as soon as each one appeared, instead of waiting for the instruction sequence to end. Additionally, the testers noted that they had trouble remembering which color corresponded to which cube, which made tilting the sequence back hard. The collaborative input, as indicated by yellow arrows, was particularly difficult for people to repeat, and they struggled to carry out the appropriate actions in tandem.

Several measures were taken to address these usability issues. Specifically, the collaborative input (as indicated by yellow arrows) was discarded from the task. The design of the presentation sequence on the LED matrices was changed such that the LED matrix scrolled “LOOK!” before the sequence began, then “GO!” to indicate that the sequence had finished, and that it was time for the users to repeat the sequence by tilting the cubes. Additionally, the neopixel lights inside each cube were programmed to statically display the color corresponding to the color of input arrows on each cube, in order to provide a constant reminder of which color corresponded to which cube. The game was tested again with different HCI researchers, which showed that these changes accounted for the usability issues with the game.

6.5.2 User study

Next, the Color Mixer activity and the Simon Tilt game were tested in the wild to see how a diversity of people understood them. Two opportunities arose where they were presented to HCI researchers through public demos at two conferences — at ACM CHI 2016 and at ACM IDC 2016. At both conferences, a stall was set up to showcase the Magic Cubes, at which people could voluntarily stop to try out the activities and discuss them with the researchers. In both deployments, a large number of people (>100 total) stopped to interact with the cubes, over a period of several hours. Notes were taken on their interactions with the cubes when trying out the game and color mixing activity. The focus was to understand what aspects of the tasks were engaging, and how people reflected on the underlying system and hardware concepts that were embedded in the tasks.

Disengagement and lack of reflection with the Simon Tilt game

It was found that many people became quickly disengaged with the *Simon Tilt* game while trying to understand the purpose of the game – even with the changes to the interface to make it more obvious what to do. Those who did understand the rules of the game engaged with the activity for several minutes, and were positive about it. Despite this, it was observed that the game did not inspire verbal reflection about the underlying concepts related to sensors, actuators and wireless connectivity. Specifically, very few people expressed curiosity about the implementation of the game, for example by asking how the cubes were connected, or how the sensors enabled the interaction. It seemed that people who interacted with the *Simon Tilt* game treated the Magic Cubes as a *medium*, through which to carry out an activity, rather than a *toolkit* for reflecting on systems and IoT concepts; their focus was on completing the game, rather than on reflecting how the system that enabled the game worked. This was possibly due to the fact that the game was **goal-based** rather than **exploratory.** It had been set up for pairs to score as many points as possible by completing ever longer sequences before getting the sequence wrong. This raised the question of how activities focusing on competing and scoring points might be more distracting than beneficial. It also raised the question of to what extent the learning activity should be abstract rather than a game that has strong associations with it, which might be difficult to detach from when thinking about the underlying concept being represented.

Engagement and lack of reflection with the Color Mixer activity

The *Color Mixer* activity led to different findings. A larger proportion of the passersby actively engaged (i.e., completed the task) with the *Color Mixer* activity than with the *Simon Tilt* game. This was perhaps because of the simplicity of the interaction, which made the activity easier to understand. It was also noted that people who engaged with the activity were consistently surprised by it when they started the interaction, as was evidenced by a number of exclamations (e.g., "oh wow!", "that's cool!") that were observed in both settings; this type of surprise did not occur with the *Simon Tilt* game. Additionally, potentially due to its exploratory and surprising nature, more people asked the researchers how the system was implemented than in the *Simon Tilt* activity. However, as in the *Simon Tilt* game, the users' focus during interaction was seen to be predominantly on the task—that is exploring ways to mix specific colors. Other than occasional questions about how the system was implemented, no explicit reflection was observed about the underlying wireless connectivity and data being transferred.

6.6 Discussion

This chapter has shown a number of challenges to consider when designing discovery-based learning activities for exploring IoT concepts with the Magic Cubes. While the initial workshop provided insights into how to constrain the interaction with the Magic Cubes and facilitate discovery of the cubes' functionality, the user study with the redesigned activities raises new questions about how best to design learning activities so that the concepts that need to be learned and understood can be abstracted from the hands-on activity. If the activity is very engrossing or tied closely to a type of game it might prove to be more difficult to abstract the concept away from the game. Finding a way of enabling the learner to step back and reflect on the underlying mapping being represented is key.

The findings from the user studies after redesigning the learning activities suggest that the *Color Mixer* activity was relatively more successful compared with the *Simon Tilt game* in terms of promoting engagement with the Magic Cubes. It also appeared to encourage more people to ask questions about how they worked and their implementation. This difference in level of engagement and curiosity seems to arise from the interaction of two factors: ease of use and the task goal. Specifically, the *Simon Tilt* game was more difficult to understand and was goal-oriented, which encouraged users to direct their focus on scoring points. In contrast, the *Color Mixer* activity was easier to accomplish and drew on familiar actions (i.e., a pouring action). The *Color Mixer* was also more open-ended which encouraged more exploration of the cubes. Hence, ease of use and open-endedness could be more conducive for providing the scaffolding for learning, i.e., enabling learners to move back and forth between the familiar physical actions afforded by the task and cubes, and their understanding of the underlying concept it is being connected with (e.g., how parts in a system connect and how they are interdependent). A challenge for the next phase of the research, therefore, was to be able to devise learning activities that capitalize on aspects of design that were found to be most successful here, especially open-endedness and ease of use, so as to foster engagement and curiosity, while at the same time encourage people to examine the IoT components of the Magic Cubes, in order to reflect on the IoT concepts instantiated in the activity. Next, I summarize how the findings were carried forward to the subsequent, empirical chapters.

6.6.1 Feeding the design strategies forward

The collective insights from this chapter, including the findings from the workshop held at the BBC and the user study carried out at two conferences, can be combined into three key design strategies for discovery-based learning activities aimed at teaching children about IoT through the Magic Cubes. Specifically, these are:

1. *Facilitating discovery of the cubes' properties through simple introductions and familiar actions.* This can be achieved, for example, by starting with a simple task that involves exploring one cube first to familiarize the children with the technology, and moving on to more complex tasks that involve multiple cubes. It can also involve capitalizing on familiar actions (e.g., shaking and tilting) to promote use and understanding of the cubes. This design strategy also has implications for the IoT topics that are chosen to teach when first starting learners out with the Magic Cubes. The findings suggest that a good strategy might be beginning by enabling learners to explore and reflect on the cubes' key hardware and functionality, like the different sensors and actuators embedded in the cubes, and only then moving on to more complex IoT topics like systems thinking.

2. *Encouraging creativity and freedom when using the cubes by making tasks exploratory.* It was demonstrated that open-ended tasks that allow for more freedom and exploration can promote more engagement and discovery of the cubes' properties, as opposed to tasks that are more constrained in terms of the actions they call for. Moreover, exploratory tasks seem to promote more reflection about the properties of the cubes, than those that are goal-based (e.g., the Simon Tilt game), as the latter can make the individual focus more on achieving the goal than reflecting on the technology itself.
3. *Providing instructions flexibly so as not to overwhelm the learner.* The design of learning activities does not just involve designing for the interaction with the technology, but also designing task-relevant materials and methods of instruction. Providing all instructions at the beginning of a learning task can be overwhelming as well as make the interaction with the cubes too prescriptive. Instead, instructions should be provided flexibly, for example through in situ guidance by an instructor, which can also support the second strategy of encouraging creativity and freedom.

Next, these three strategies were used to inform the design of the learning activities created for the classroom studies, which are presented in the next three chapters of the thesis. Although through the chronological process of carrying out and reflecting on each subsequent study, other design strategies were also adopted, the three summarized above were key in all three of the classroom studies. The full details of the learning activities for each of the classroom studies are provided in Chapters 7, 8 and 9, however, Table 6.2 below summarizes how these strategies were used to design the activities.

Table 6.2: A summary of how the design strategies derived from the research in this chapter were adopted when designing tasks for the studies in Chapters 7, 8 and 9.

Chapter 7: **Target learning outcomes:** To teach conceptual understanding of sensors and actuators and how they work, by asking children to uncover a variety of sensor-actuator mappings embedded in the Magic Cubes. These include, for example a mapping between the speed of acceleration and the colour of light emitted by the cube, and a mapping between the temperature sensed by the cube and the animation that the cube displays. **Application of design strategies:** 1. *Facilitating discovery of the cubes' properties through simple introductions and familiar actions*: As opposed to the initial tasks designed in this chapter, where users interacted with two interconnected cubes at a time, only one cube at a time was provided to the children. This was done to make it easier for the children to understand the sensors and actuators embedded in the Magic Cubes when first interacting with them. In addition, the effects were designed to be highly visible and noticeable with certain physical actions, in order to facilitate the discovery of the embedded mappings. 2. *Encouraging creativity and freedom when using the cubes by making tasks exploratory*: The tasks were designed so that there was no right or wrong way to discover the mappings, and no explicit instructions were given about how to go about eliciting a mapping. For example, discovering the functionality of the light sensor in the Magic Cubes could be achieved through a variety of actions like hiding under a desk or by covering the light sensor with a fingertip. 3. *Providing instructions flexibly so as not to overwhelm the learner*: The instructions were provided only verbally, rather than in written form, and instructors walked around the classroom to help children who asked for support or were struggling with the tasks.
Chapter 8: **Target learning outcomes:** To foster higher-level critical thinking about the act of sensing and the reliability and accuracy of sensors. This was done by creating discovery-based activities where the children were able to explore data from different sensors, and relate this to aspects of their bodies (i.e., their pulse, stress level and step count) and the environment (e.g., ambient temperature, light level). By doing so, the aim was to enable them to reflect on when sensors are inaccurate, unreliable and what this means in terms of trusting sensors in IoT systems in general. **Application of design strategies:** 1. *Facilitating discovery of the cubes' properties through simple introductions and familiar actions*: In order to facilitate the children's discovery of the Magic Cubes, each cube was programmed to have only one function – for example, some cubes were programmed to act as a pulse sensor, and others as a pedometer; each cube was also labelled in terms of its programmed function. The goal of this was to encourage the children to focus on only the mapping programmed into each cube at one time, rather than exploring everything the Magic Cubes could do. The children were also provided with written tips for getting started with the sensors in order to facilitate understanding. 2. *Encouraging creativity and freedom when using the cubes by making tasks exploratory*: The children were encouraged to be creative when deciding how to test the sensors' capabilities – for example, they were able to choose whether to walk, dance or jump with the pedometer to test when it was most accurate. In order to support creativity, the children were also provided with suggestions for what to explore, which they could choose whether or not to try (e.g., using a cube sensing Galvanic Skin Response as a lie detector). **3.** *Providing instructions flexibly so as not to overwhelm the learner*: While the children were provided with written tips and suggestions for how to explore the sensors, similarly to the setup in Chapter 7, instructor guidance was provided in situ and the instructors walked around the classroom to periodically support all the children in the discovery process.
Chapter 9: **Target learning outcomes:** To introduce special education needs students (a different demographic than that in Chapters 7 and 8) to the conceptual understanding of sensors and actuators and how they work, and further to enable them to combine this conceptual understanding with programming and design thinking, in order to integrate these introductory IoT concepts with broader computational thinking skills. **Application of design strategies:** 1. *Facilitating discovery of the cubes' properties through simple introductions and familiar actions:* The introductory discovery tasks were the same as those presented in Chapter 7. Facilitating discovery of the cubes' properties was further built on through tasks that involved discovering mappings between wirelessly interconnected cubes, after discovering mappings for one cube at a time. 2. *Encouraging creativity and freedom when using the cubes by making tasks exploratory*: The same principles were applied as those in Chapter 7. Further, following introductory discovery tasks, the students were asked to complete programming tasks with the Magic Cubes that included an element of creativity, for example making an animation of their choosing. 3. *Providing instructions flexibly so as not to overwhelm the learner:* Guidance was provided in situ, by instructors who walked around the classroom to offer support. To suit the needs of this group of students, a higher ratio of instructors to students was adopted than in the other studies.

6.6.2 Reflection on the evaluation methodology

The outcome from the initial workshop also helped to determine which evaluation strategy to use for subsequent research when assessing what students learn about IoT. Initially, the idea of using pre- and post- assessments was proposed as a way of measuring how much students would learn when interacting with the Magic Cubes. However, in the initial workshop it was found that coupling learning tasks with written pre- and post- tests was off-putting before embarking on a discovery activity and also potentially inappropriate, depending on the design of the test. Specifically, asking the students to define abstract concepts that they had likely not been exposed to before in a pre-test does not seem an informative way of assessing what knowledge they have gained. Moreover, during both the initial workshop and the user study, observing how the participants interacted with each other and with the cubes was revealing in terms of how successful the learning activities were and why. Therefore, for the subsequent studies in this thesis, it was decided to focus on how to analyze the learning process itself.

The reason for this switch in methodology is that it was assumed to be more insightful, in terms of understanding what aspects of the task are engaging, difficult, conducive to reflection and why. For the first in-school study (Chapter 7), it was decided to adopt the methodological approach of observation followed by video-based analysis of interactions, focusing on assessing learning as a process, rather than on what students know before and after a learning intervention. The pros of using this method are that it is more informative in terms of understanding how a designed learning activity contributes to learning about the target concepts and topics. It also enables closer examination of how different support structures that are in place during the activity can affect the learning process, beyond a task with the physical toolkit itself – for example, how instructions are presented and the level of instructor guidance that students receive throughout the activity. The cons of not using a pre- and post- test, however, is the assessment is not as systematic, and how to devise the right analytic framework to use is not straightforward. The findings in the next study are presented as qualitative accounts, arguably providing deeper insights into the way that students interact and learn, but a less robust account of the knowledge the students have gained.

6.7 Summary

This chapter has described the context and motivations for using the Magic Cubes in this research. Moreover, the chapter has discussed how initial discovery-based learning tasks for learning about IoT were designed and evaluated. The initial designs were iteratively evaluated through a workshop and a user study in public spaces. The evaluations revealed a number of strategies for designing discovery learning tasks that are engaging, collaborative, and might encourage reflection about the target IoT concepts.

Specifically, initial introductions to the Magic Cubes toolkit should start with the fundamental concepts of sensors, actuators and the mappings between them and then build on these, in order to facilitate discovery of the cubes' functionality and properties. While the researchers in the initial workshop argued that capitalizing on familiar games and metaphors may be a promising design strategy, further prototyping and evaluation of other learning tasks showed that this could impede reflection. It was also found that designing for open-ended, rather than goal-oriented exploration may promote more engagement.

The feedback from the workshop and user testing raises a number of research questions. The three main ones that were subsequently addressed in the thesis are: *(i) which kind of task is most effective in promoting reflection on IoT topics?, (ii) what is the value of discovery learning about IoT topics?,* and *(iii) what is the best way to qualitatively evaluate the learning process?*

CHAPTER 7: THE ROLE OF EMBODIED INTERACTION IN COLLABORATIVE DISCOVERY LEARNING

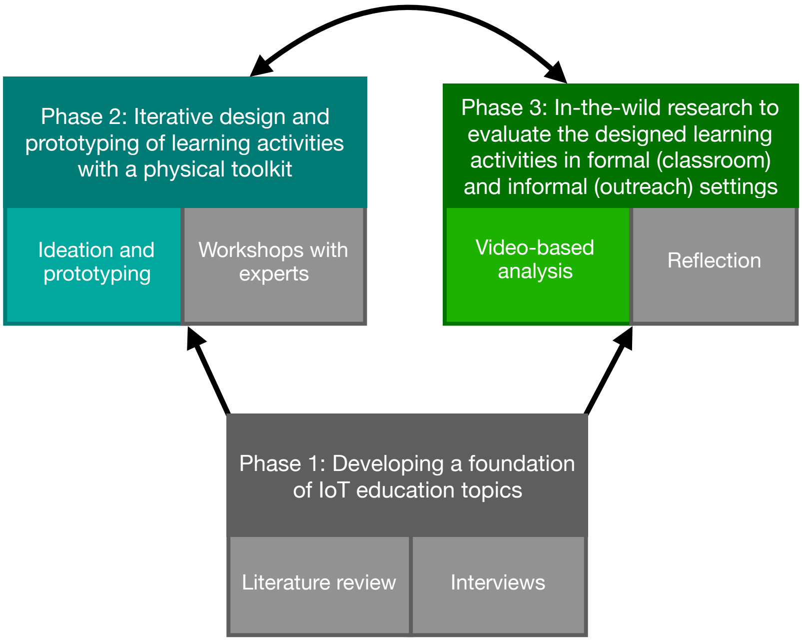


Figure 7.1: This chapter 1) addresses the redesign of introductory discovery-based learning activities, and 2) presents the first in the wild study carried out in a classroom setting, together with video-based analysis.

Following the initial design and evaluation phases which explored how the Magic Cubes might be used to teach IoT topics, the next phase of the research involved 1) redesigning the introductory, discovery-based tasks with the Magic Cubes to teach about the concepts of sensors, actuators, and the mappings between them, and 2) evaluating how children interact and learn about these concepts when using them in an ecologically valid setting. A focus of the evaluation was to assess how engaging the new discovery-based tasks were and the extent to which they engendered collaborative learning. A further aim was to address the research question of whether and how using the Magic Cubes supported embodied interactions, and if so, how this can support learning about a particular aspect of conceptual understanding related to IoT – namely, the way different sensor and actuator components connect and work together. It was decided to carry the study out in real primary schools, to determine how children observe and learn from each other in a large group setting that is typical of a classroom.

Three new introductory, discovery-based tasks were designed for the basic IoT topic of sensor-actuator mappings. These were pre-programmed onto the Magic Cubes prior to the study. The children were asked to uncover the three sensor-actuator mappings embedded in the Magic Cubes in pairs or groups of three, in order to encourage collaboration. The methodology used was to video record the children using the cubes in a classroom setting, sitting at their desks. The analysis focused primarily on the groups' embodied interactions when using the Magic Cubes. The contribution of this study is to demonstrate how a variety of embodied interaction strategies emerged in the context of the specified learning activities, and how these enabled the manipulating, sharing, showing and experimenting with the cubes that supported learning about IoT concepts.

7.1 Motivation and Research Questions

There is much evidence that embodied and physical interaction during discovery learning can encourage cognitive processes, such as sense-making and knowledge integration [Price & Falcão, 2011]. However, questions still remain as to how the affordances of the new generation of physical computing interfaces contribute to the collaborative learning process, and conversely, how they can be better designed to support it. Much research has indicated that physical and tangible interfaces can foster collaborative behavior and understanding (see [Antle & Wise, 2013; Suzuki & Kato, 1995]). The focus of research that has investigated collaborative learning with tangible interfaces for teaching computing has been largely in terms of measuring performance outcomes such as the proportion of the task time spent collaborating [Johnson et al., 2016], or number of individuals with whom a particular learner collaborated [Horn, Crouser, & Bers, 2012]. There has been little research reporting on how the collaborative learning takes place, in terms of what kinds of shared, embodied interactions arise when learning computing with the next generation of physical toolkits.

It is proposed here that an alternative approach is needed to reveal more about what actually happens—one that examines what children do at a finer level of analysis. To this end, this study specifically examines the coordination and sharing strategies children adopt and use when exploring the physical properties of the Magic Cubes. An assumption is that these kinds of micro-level embodied interactions are integral to how collaborative and embodied learning takes place. It is one thing to count the length of time someone collaborates or how many collaborative partners a learner has. It is another to understand more fully how they were able to do this, given the affordances of the interface and the type of learning activity. Therefore, the micro analytic lens adopted here was to examine in detail how children grasp, handle and manipulate the physical properties of the Magic Cubes when using one in pairs or groups of three, and how this constraint gives rise to their ability to reflect on what they are learning about. The specific research questions addressed were:

RQ 7.1: *What kinds of embodied interaction strategies do children use together during collaborative discovery with the Magic Cubes and what do they learn when engaged in these? For example, do they use the physical affordances to show, point to, and share connections together?*
RQ 7.2: *Do the types of embodied interactions that they choose to employ change throughout the task?*

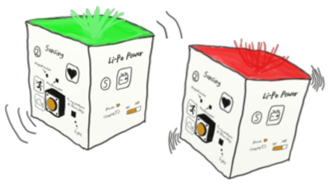
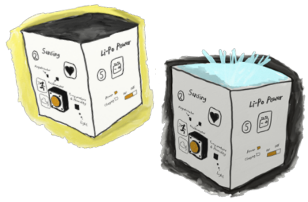
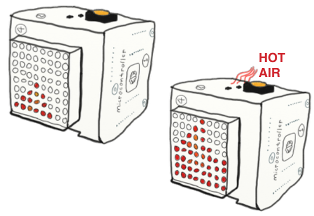
7.2 Redesign of the Introductory Discovery-Based Activities

Based on the findings from the workshop described in the last chapter, it was decided that instead of using the proposed systems thinking concepts as a starting point, the more basic concept of sensor-actuator mappings (e.g., a mapping between the speed of acceleration and color of light) would be used - that could be explored using a single Magic Cube. The reason for this decision was that it was considered more appropriate to design an introductory learning activity that was not too challenging for children when first introduced to the cubes, and limited what they had to discover. For example, instead of discovering the connections between sensors and actuators in two wirelessly connected cubes, they were able to focus first on understanding how the sensors and actuators work together in just one cube. The discovery-based structure of the tasks, which was found in the workshop to be both appropriate and engaging, was kept.

A number of sensor-actuator mappings were designed for the Magic Cubes, and programmed onto the cubes using the Arduino programming environment. These mapped the data collected by the light, temperature, and acceleration sensors on the cubes to different light effects – for example, various animations on the LED matrix and various colors on the internal neopixel light. The designed mappings were tested and iterated on before being given to the children. This was done in the lab with four HCI colleagues, and in an extracurricular public outreach session with a number of visitors. Throughout the prototyping and testing process, several issues with the initial mappings that were created were addressed. For example, the algorithms that detected valid sensor input (e.g., tilting the cube, shaking it), were modified to account for the fact that people's interactions with the interface were often imprecise.

This iterative design process resulted in a final set of three introductory discovery tasks being selected to give to children to explore. These comprised simple, medium and more complex mappings in terms of the sensor used, physical action required, and the resultant digital effect (see Table 7.1). The reason for varying the level of complexity in this way was because the aim was to make each task increasingly challenging to see how well the children coped with an increase in difficulty. The mappings that were selected were also those where the actuated effects, and physical actions required to elicit these effects, were most visible. Based on the observations in the workshop (see Section 6.4), high visibility of both physical actions and digital effects was assumed to help learners build an awareness of each other's level of understanding during the process of discovery. The selected mappings also employed different spatial affordances of action and effect, which were assumed to elicit different types of embodied interactions. For example, with the Build-a-Fire mapping, which requires a person to blow hot air into the sensor on the cube, it is difficult for two people to interact with the cube simultaneously. In contrast, with the Night Light mapping, in which the digital effect can be elicited in a variety of ways (e.g., by putting the cube under the table, or by hovering a hand over the sensor), it is feasible for more than one person to interact with the cube at once.

Table 7.1: **The three redesigned introductory tasks comprising sensor-actuator mappings.**

(a) Shake-a-Color	**(b) Night Light**	**(c) Build-a-Fire**
		
Description: The speed of acceleration maps to the color of light inside the cube (e.g., shaking the cube slowly produces a green light; shaking the cube very rapidly produces a red light)	**Description:** A binary mapping, where placing the cube in a dark place or otherwise covering the light sensor turns on a white light inside the cube.	**Description:** A binary mapping, where blowing hot air into the temperature sensor creates a bigger "fire" animation
Implementation: Sensor: accelerometer; Physical Action: shaking; Digital effect: change of color in neopixel light	**Implementation:** Sensor: light; Physical Action: hiding, covering; Digital Effect: white neopixel light turns on	**Implementation:** Sensor: temperature; Physical action: blowing; Digital effect: change in animation on LED matrix
Scaffolding: Easiest mapping to discover; calls on familiar physical actions (i.e., movement and shaking), and does not require localization of the sensor.	**Scaffolding:** More difficult mapping to discover, as understanding it requires working out where to find the light sensor on the cube.	**Scaffolding:** Most difficult mapping to discover; requires precise localization of the sensor, and an unfamiliar physical action (i.e., blowing hot air into an interface)

7.3 Methodology

An in the wild study was designed to examine how pairs or groups of three school children interacted during the three discovery-based learning activities, focusing on how they collaborated.

7.3.1 School context and participants

The study was conducted in two schools in London: a mixed gender school (n=97), and a girls-only school (n=48). Participants were aged between 9-12 (mean=11). This age range was chosen as according to the UK computing curriculum it is when they are expected to start learning about the relationships between hardware and software [UK Department of Education, 2016]. Both participating schools were recruited based on their prior collaborations with UCL Engineering, and their interest in expanding their computing provision. The study took place during 6 classroom sessions (4 in the mixed gender school and 2 in the girls-only school), each with a different group of participants.

The first school was a mixed gender, community school with a total number of approximately 900 pupils between the ages of 3 and 11 and an average class size of 30. The school is situated in a city context, in an outer borough of London, with 14.2% of pupils eligible for free school meals. A total of one teacher and 97 children across four class groups, who were all in Year 6, participated. Four separate sessions were run, one for each class group; given this, the children in each session all knew each other and were familiar with each other from other group work. All of the sessions were carried out in the school's dedicated computer room.

The second school was an all-girls independent school with a total number of approximately 1,100 pupils between the ages of 4 and 18. The school is situated in a city context, in an inner borough of London, with no pupils eligible for free school meals. A total of one teacher, 24 children in Year 5 and 24 children in Year 6 participated in the study. Two separate sessions were run – one for the Year 5 children and one for the Year 6 children, although the content of the sessions was the same. The children who participated in the session were chosen to do so by the school, on the basis of their interest in computing; therefore, the children were not in their typical class group. However, they all knew each other from other group work in school as well as, for some, from working together during their extracurricular computing club.

Neither of the schools had previously integrated lessons about IoT topics, specifically, into their computing curriculum. However, within the school curriculum, the children in the girls-only school had been exposed to sensors and actuators by experimenting with other physical computing toolkits. In contrast, in the mixed gender school the children had not yet been exposed to physical toolkits with sensors and actuators as part of the school curriculum.

In all sessions, the children were asked to work in groups of two or three. The children all chose their own partners/groups; in rare instances where the teacher expected a specific pair/group to be disruptive, they reshuffled the pair/group.

7.3.2 Procedure

To enable the children to all have the same level of conceptual understanding, each session began by the researcher explaining what sensors and actuators are. The children were asked to define the terms in relation to real-world examples and metaphors. The researcher was there to help for this part of the activity.

The cubes were then introduced to each group/pair. One cube was provided for each pair/group. This was done in order to encourage collaborative rather than independent discovery. The children were asked to look at their cube to see what components were embedded in the Magic Cubes (e.g., light sensor, temperature and humidity sensor, accelerometer, LED matrix). To make the concept of a sensor-actuator mapping concrete, they were instructed to shake the cube for the first discovery task (thereby eliciting the *Shake-a-Color* mapping), and asked to explain to the others what was happening in terms of the sensor (accelerometer) and actuator (light). The children were told there were two further *hidden mappings* within the cube (the *Night Light* and *Build-a-Fire*), which included some of the other sensors. Their challenge was to collaboratively discover them by testing out various physical actions to elicit the digital effects on the cube. The activity was not time constrained; the participants were asked to carry out the tasks in their own time. No paper materials were provided to help them proceed; all instructions were provided verbally.

7.3.3 Data analysis

A set of cameras was set up in each classroom to record the children's interactions with the cubes, with the consent of both the participants and their parents. Both close and long shots were recorded, in order to closely monitor collaboration both within and between groups. The aims of the analysis were to investigate (i) what types of embodied interaction strategies the children used during the discovery process, and (ii) how they used the cubes to negotiate a shared problem space. The form of analysis employed was micro-level coding of interactions, which was based on the foundations of the Interaction Analysis approach. By this is meant that the analysis emphasised the social and material context in which the children's interactions took place; that the micro-level codes were placed in context of where they occurred in the more macro-level structure of the tasks; and that the codes formed by first creating a content log of video data and subsequently viewing it iteratively to understand the structure and context of events in the video.

As conducting a micro-level analysis produces very rich data, 5 groups of participants (N=11) were selected (see Table 7.2 for detail about the selected groups). To choose these participants, the candidates for analysis were first narrowed down by creating a subset of the participant pool. This included all the groups in which the video data showed consistent visibility of the participants' interactions with both each other and the cubes. From this subset, 5 groups were chosen whose interactions within the groups were seen to be representative of the interaction patterns of other groups—based on discussions between myself and another researcher after watching the video multiple times and discussing collaborative trends.

After selecting the groups to be analysed in detail, I watched a subset of the videos together with another researcher in order to create a shared classification scheme of the collaborative, embodied interaction strategies that the children used when completing the task. I then coded the data based on the classification scheme. Annotations were made about individual participants' attention to the task, as indicated by their eye gaze. The focus was on the gestures and interactions used; where audible (a class of 20-30 children talking made it hard to consistently discern what each was saying from the video cameras) the dialogue was transcribed.

To add structure and context to the coded data, the children's task trajectories were broken down into five phases that all groups were seen to consistently follow. The micro-level codes of embodied interaction strategies were annotated in terms of these macro-level phases in which they occurred. This provided context to the micro-level codes and enabled analysis of the context in which specific embodied interaction strategies occurred during the task.

Table 7.2: Summary of the participants in the groups chosen for analysis.

Group Number	School	Participants
1	Mixed gender, state school	3 boys
2	All girls, public school	2 girls
3	All girls, public school	2 girls
4	Mixed gender, state school	2 boys
5	Mixed gender, state school	2 girls

7.4 Findings

Each group took between 10-15 minutes to complete the activities. Overall, the results showed that the children used a range of embodied interaction strategies when using their cube to discover the mappings, that varied depending on how far along they were in the task. In particular, it was found that when starting with discovering a new sensor-actuator mapping, the participants mainly took explicit turns in handing the cube over to each other or grabbing the cube from their partners. As they progressed with the activity, their embodied interaction strategies became more varied, and the way in which they changed control and took turns with the cube became less explicit. It was found that the visible nature of both the actuated light effects and the physical actions required to elicit them was conducive to watching their partner(s) and other groups around the classroom, and imitating what they had done. An unexpected finding was how often children switched from working within their pair/group to observe and show others in the classroom.

The findings also revealed that two groups used distinctive collaboration styles, where group members either explored the mappings almost wholly individually (Group 2), or largely collaboratively (Group 3), whereas the groups that mixed the two styles

(Groups 1, 4 and 5) had more success in discovering the mappings independently of help from others. Next, the nature of the embodied interaction strategies and collaborations throughout the task are reported.

7.4.1 Classifying embodied interaction strategies and discovery phases

A micro-level coding method was used to classify the types of embodied interaction strategies the children employed throughout the session. Six distinct strategies were identified, three tied to explicit changes in control and three tied to non-explicit changes in control (see Table 7.3 and Figure 7.2). By explicit changes of control is meant clearly expressed changes in the individual presently holding the cube. By non-explicit changes of control is meant that control is changed more indirectly. Another researcher verified instances of the six strategies by viewing a sample of the video transcripts.

In order to understand the context in which these embodied interaction strategies occurred, the way the participants carried out the discovery tasks were then categorized in terms of 5 phases. This classification was derived from an iterative analysis of the video data of the children's use of the cubes:

(i) *General Exploration:* To begin, the pairs/groups of children spent time examining the cubes by looking at each side and then testing out various physical actions, without directing their interactions at uncovering a specific mapping.

(ii) *Partial Discovery:* This phase was characterized by an incomplete understanding of a specific mapping, and occurred when a digital effect was elicited for the

Table 7.3: A description of the six embodied interaction strategies arising from the analysis. The embodied interaction strategies presented in dark blue correspond to those tied to explicit changes of control, whereas those presented in light blue correspond to non-explicit changes of control.

Interactions tied to Explicit Change of Control

(i) **Handover:**
Transfer of control of the cube, initiated by the current grasper*

(ii) **Grab:**
Transfer of control of the cube, initiated by the current non-grasper*

(iii) **Pull-away:**
An attempted grab, obstructed by the current grasper

Interactions tied to Non-Explicit Change of Control

(iv) **Set-down:**
Placement of the cube on a neutral surface, for example the desk

(v) **Pick-up:**
A pick up of the cube from a neutral surface

(vi) **Situated manipulation:**
A manipulation of the cube by a non-grasper, without transfer of control. This could occur either when the cube was held in the air by the grasper, or when it was set down on a neutral surface.

***In this classification, the *grasper* is the individual currently holding the cube, whereas a *non-grasper* is an individual not currently holding the cube.**

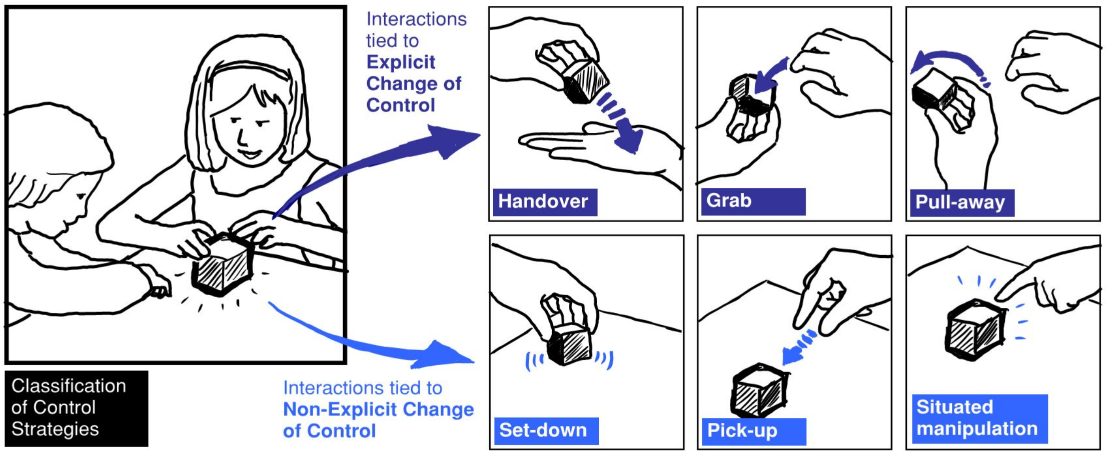


Figure 7.2: A visual representation of the six embodied interaction strategies arising from the analysis.

first time. Usually, it was identified by attention to the digital effect (e.g., the animation on the LED matrix), without attention to the sensor (e.g., temperature sensor), along with an inability to reproduce the physical action that led to the digital effect

(iii) *Directed Exploration:* This occurred after reaching partial discovery of a mapping, as a way of trying to fully discover it. An example constituting directed exploration was examining the cube in an effort to localize the temperature sensor to elicit the change in animation within the Build-a-Fire mapping.

(iv) *Full Discovery:* This occurred at the end of directed exploration and involved intentionally reproducing the digital effect through directed action on the sensor. The stage was characterized by successful localization of the sensor, and attention to both the sensor and the digital effect.

(v) *Extended Exploration*: This was characterized as repeated reproduction of a mapping after full discovery. Often, the repeated reproduction became increasingly creative (e.g., dancing with the *Shake-a-Color* mapping).

For each of the tasks, the children were seen to move from one phase to the next. These discovery phases were used subsequently as a basis through which to discuss how the embodied interaction strategies unfolded in the discovery task.

7.4.2 General exploration

The general exploration phase, at which no previous experience of the mappings yet existed, was mostly tied to explicit turn-taking behavior. Specifically, in this phase, the children in all groups were seen to take turns independently trying out various physical actions with the cube, and to explicitly **handover** and **grab** the cube to and from their partners. Mutual attention to the task, as indicated by eye gaze toward the interface and other group members, was present.

7.4.3 Moments of discovery

The analysis revealed that the phases of both partial and full discovery were characterized by similar patterns of embodied interaction strategies, which helped group members achieve the same level of understanding by observing others and trying the action out themselves. Within groups, when one child discovered the functionality of a mapping – either partially or fully – **rapid sequences** of handovers and grabs ensued, in which the other(s) imitated their visible physical movement. **Handovers** were most prevalent when the grasper (the individual currently in control of the cube) had reached the partial or full discovery phase, while the other(s) in the group had not. In other instances, handovers were used as a "show me" indicator, where the grasper was aware that the other(s) had a higher level of understanding of one of the mappings. Although **grabs** were similarly tied to leveling understanding between group members, these were less frequent than handovers, and more often they were present during directed exploration.

Within moments of discovery, **situated manipulations** were also tied to imitating physical actions leading to the mappings, however, this was dependent on the spatial affordances of the mappings. Specifically, situated manipulations occurred only when eliciting the digital effect of the mapping did not require the cube to be picked up and held close to the body. For example, when an individual holding the cube figured out the location of the light sensor within the Night Light mapping, it was often observed that the other(s) reached out to touch it and reproduce the digital effect. Within the Build-a-Fire mapping, handovers were more frequently used to share understanding than situated manipulations, because the cube had to be held by the participant's face to reproduce the mapping.

The handovers, grabs and situated manipulation at moments of discovery were found to occur across all the groups. It was found, as assumed, that the physicality of the actions required to elicit a mapping, coupled with the high visibility of the corresponding digital effect often led to others stopping what they were doing, and switching their attention to observe and then imitate what their partner or other group had just discovered.

7.4.4 Directed exploration

Directed exploration was the phase where most between-group differences were observed, and was tied to varying collaboration styles. In three of the groups (G1, G4, G5) a range of **individual** and **shared sequences of action** were observed during phases of directed exploration. Here, **individual sequences of action** are described as instances where only the current grasper is in control of the interface, whereas **shared sequences of action** involve more than one group member simultaneously interacting with the interface (i.e., through situated manipulations).

Importantly, during sequences of individual action in directed exploration, in all but one group (G2), shared attention, as identified by eye gaze, was near constant. This enabled the children to monitor each other's physical manipulations of the cubes throughout the exploration and to initiate strategies for changing control at appropriate moments in the task. The most frequent embodied interaction strategy during individual sequences of action was **grabbing** the cube from the current grasper. This was observed to be an indicator of change of an exploration trajectory. For example, in Group 4, the non-grasper observed another group blowing into the cube and therefore eliciting the Build-a-Fire mapping. She grabbed the cube from her partner to attempt to imitate the physical action that the successful group had employed. Where the current grasper was in the midst of trying out a specific, usually previously untested, physical action, attempted grabs resulted in **pull-aways**.

Additionally, directed exploration was the phase in which **set-downs** and **pick-ups** occurred most frequently. These were indicators of change of turn for control of the interface. They were observed to commonly occur during "dead ends" in interaction, where a type of physical action did not work as expected. For example, after tilting the cube in a variety of different directions to no avail, when trying to figure out which sensor was making the light turn on (in the Night Light mode), the current grasper in Group 1 set it down on the table, where another group member quickly picked it up and began exploring other physical actions.

Sequences of shared interaction (i.e., through **situated manipulations**) occurred most frequently directly after a partial discovery, where the digital effect had been discovered, but the physical action required to achieve it had not been. In these sequences, groups frequently examined the cube together, with both/all members touching the various electronic components simultaneously, without explicitly changing control. These sequences of shared action enabled the children to collaboratively test hypotheses that enabled them to reshape their understanding of the mapping functionalities. For example, after observing another group placing the cube under the desk in the Night Light mode, Group 1 mimicked the movement, noticing that in doing so the embedded light turned on. One group member concluded that in this mode, the light only turned on in the darkness. However, another group member was unsatisfied with this explanation, having previously noticed that tilting the cube toward a flat surface also served to turn the light on. He instead posited another hypothesis: that the cube "knows distance with a laser", and that the light turned on when something was sufficiently close to the hypothesized distance sensor. The group then spent several minutes testing out both hypotheses by collaboratively hovering their hands around different sides of the cube at varying distances, examining the sides more closely, and seeing in what cases the light turned on. Eventually, one member discovered that the light turned on only by covering a particular side of the cube. They then noticed the arrow pointing to the light sensor, and used only their fingertips to cover it, localizing the component.

Another common occurrence during directed exploration was watching and imitating **between** (i.e., across) groups, which occurred in both school settings. The tie between highly physical movements and visibility of the effects enabled the children to easily monitor what other groups were doing, which often led to waves of similar interface manipulations across the classroom. For example, in one classroom, one group figured out the Build-a-Fire mapping functionality by blowing into the temperature sensor. The effect of the change in animation was highly visible to nearby groups, and within a minute, all groups in the vicinity were blowing into the cube. However, as hot air had to be blown directly into the temperature sensor, individuals subsequently had to continue independent exploration to figure out the precise location of the sensor on the cube, as well as the effect of different temperatures of air.

7.4.5 Extended exploration

It was observed that in the videos of three of the five groups analyzed (G1, G4, G5), during the extended exploration phase where a full understanding of the mapping had been reached, the children's interactions became more creative. This was evidenced by what was said and done. For example, several girls danced around the room showing off their Shake-a-Color mapping, giggling at the rapidly changing colors of light as they moved. A boy took a sip of cold water to make his breath cold and blew into temperature sensor, in an effort to see if the fire on the LED matrix would "go out" completely. Many of the children also showed curiosity in the data underlying the sensor-actuator mappings, asking the researcher how the cube "knew" how quickly it was moving, and discussing how the Build-a-Fire and Night Light mappings could be extended to measure non-binary levels of light and temperature.

Increased interactions between groups were also observed during this phase. Children leaned over to their neighbors to show them a particular pattern of light they had discovered within the Shake-a-Color mapping, and jumped up towards the light with the cube along with those sitting near them in the Night Light mapping. Several groups also playfully "competed" with nearby groups, contesting to see who could show off how the mapping worked first. For example, when another group snatched the cube from Group 1 in order to show them how the Build-a-Fire mapping worked, a member of Group 1 immediately grabbed the cube back, and demonstrated that he was able to elicit the digital effect, and showed off by sticking his tongue out when the animation changed.

7.4.6 Differences between groups

A number of differences were found in the way the groups chose to collaborate suggesting individual differences across pairs/groups. These were most pronounced in the directed exploration and extended exploration phases. In particular, it was found that in G1, G4 and G5, all members a) attended to the task and each other continuously, and b) used a mixture of explicit and non-explicit change of control styles during **directed exploration**, as discussed above. In doing so, they mixed both independent exploration and shared knowledge building.

Two groups, however, employed different strategies. G2 employed an independent turn taking strategy, which was characterized by numerous grabs, pull-aways, set-downs and pick-ups, with few handovers and no situated manipulations. Additionally, for most of the task, it was found that the non-grasper was not attentive to the grasper during the phases of general, directed and extended exploration. The group for the most part followed independent trajectories of exploration, except for moments of discovery, at which eye gaze and imitating the other member was observed.

G3, in contrast, quickly adopted a strategy where both group members could observe and step in to have a go. They designated their desk as a neutral space from which the cube could be touched. The majority of interactions were situated manipulations, whereas few grabs and handovers occurred. When one member tried to pick the cube up for a more extended period of time, the other tapped the desk to indicate their time was up and they should put it down so that they could both interact with it together. This strategy had the effect of constraining the range of physical actions that could be explored for a full understanding of the mappings. It was noted that in G2 and G3, all of the discoveries of mappings came from external sources, like observation of nearby groups or from hints from the instructor. Additionally, in these groups, **extended exploration** was limited.

In the next section, I discuss the findings in terms of the research questions posed and propose design implications.

7.5 Discussion

The discussion is structured in terms of the two research questions posed at the beginning of this chapter, namely:

> ***RQ 7.1:*** *What kinds of embodied interaction strategies do children use together during collaborative discovery with the Magic Cubes and what do they learn when engaged in these? For example, do they use the physical affordances to show, point to, and share connections together?*
> ***RQ 7.2:*** *Do the types of embodied interactions that they choose to employ change throughout the task?*

RQ7.1: What kinds of embodied interaction strategies do children use together during collaborative discovery with the Magic Cubes and what do they learn when engaged in these?

The findings from the video analysis showed how the children used a range of embodied interaction strategies when working out the connections between physically manipulating the cube and the digital effects. This suggests that the process of discovering the novel mappings through using embodied and familiar actions enabled the children to use either an explicit or implicit theory to reflect on what causes the changes of states [Rogers, Scaife, Gabrielli, Smith, & Harris, 2002]. While in this study, little dialogue could be transcribed, the way the children were able to progressively learn how to intentionally elicit the digital effects through trial and error, suggests that the variety of physical actions they used enabled them to formulate and progressively refine theories about how the sensor-actuator mappings worked.

The children also spent much time collaboratively experimenting with the cubes using different kinds of embodied interaction strategies – including handing over, grabbing, and interacting with the cube together. This seemed to be supported by how easy it was to change control of the cube from one person to another. While it was envisioned that children would work together during the discovery task when using one cube, it was surprising to see just how much joint attention took place, by way of overhearing, observing each other, sharing, pointing, and demonstrating to each other both within their group and across the classroom at large. The way the learning process was made visible through the embodied interactions appeared to encourage the children to mimic and build upon what others, both within and beyond their groups, had discovered.

RQ7.2: Do the types of embodied interactions that the children choose to employ change throughout the task?

The answer to this is yes, as revealed by the variance of the embodied interaction strategies when examined in context of the 'discovery phases' that the groups engaged with. At first, the children took longer turns interacting with the Magic Cube individually, and then changed control of the cube within their groups. Once they had worked out how to intentionally elicit a digital effect, they were proud to show this off to others, and demonstrated to their peers. In turn, this led to sequences of rapid changes of control, in which the children were seen to repeatedly hand over or grab the cube to imitate each other's actions. The finding that imitating their partners occurred frequently at moments of discovery is likely to be because of the way that the task was framed as a way of solving a puzzle together; thus, once one person figured out how to elicit an effect, they showed off what they had discovered to their partners and all wanted to have a go. When the discovery was still partial – that is, when a digital effect was discovered but the children were not sure how to intentionally produce it – the shared attention that ensued encouraged pairs/groups to continue experimenting with the cubes together. A factor that played a central role in the embodied interaction strategies that the children employed was the shape and size of the cube. Its hand-sized design was the right shape to encourage many changes of control.

There were few instances of explicit competition or fighting for control when interacting with the cubes. While the children frequently grabbed the cubes from one another, this rarely led to further competition over whose turn it was. This is in contrast to previous research where children were constrained to working together at a shared tabletop [Fleck et al., 2009]. A reason for this could have been that they were less constrained in how they worked together when using the cubes. Eliciting the sensor-actuator mappings only required short actions, rather than a longer sequence of steps. Because of this, when deciding to try something new out, the children did not need to disrupt someone else's work – for example by removing parts of a design as happened in the tabletop studies – but instead could take a cube from their peers at any stage of the task, without undoing the others' work. If anything, the impact of grabbing a cube from a partner was positive, allowing the other to watch on and then have a go. As demonstrated in the findings, even grabs and pull-aways, which might have been viewed as being un-collaborative when not examined in context of the discovery process, were able to positively direct collaborative learning. Hence, this finding contrasts with earlier research for other kinds of physical interfaces, such as tabletops, where a high incidence of competitive gestures have been exhibited especially when they are constrained for who and how many can interact with them [Marshall et al., 2009; Speelpenning, Antle, Doering, & Hoven, 2011].

Given the observation that the majority of interactions started with individual turn-taking during the general exploration phase, and quickly became increasingly more varied and shared after partial discovery of the sensor-actuator mappings, the collaborative behavior reported here may be partially tied to how the task itself was set up for the children to discover the unknown mappings. The level of suspense at what might be discovered may have also encouraged the children to switch their attention more often to observe each other's actions closely.

Another finding was that all the children in the two schools showed much curiosity about hardware, sensor-actuator mappings and the nature of data, especially during the extended exploration phase of the discovery process. This suggests they wanted to know more about how the sensor-actuator effects worked. Having discovered the mappings, they asked the instructors how the cubes "knew" what level of light and temperature the sensors were sensing. Their creativity was also evident from their discussions of how the sensor-actuator effects could be changed to apply in other ways to real life. Taken together, the curiosity and creative appropriation of the cubes are positive, suggesting that the three learning tasks were at the right level and able to provide a good foundation and motivation for learning about other IoT concepts, for example, learning how to program sensors and reflect on the accuracy of real time sensor data.

To conduct such a fine-grained analysis of micro-level interactions required much time-consuming transcribing and coding. To manage the process only very small timescales of interactions could be looked at in detail. This may have introduced bias as to the types of segments that were scrutinized. For example, looking at other types of embodied interactions beyond those chosen (i.e., grabbing, handing over, etc.) may have revealed different patterns of interaction and collaboration. However, choosing only small segments is a common approach adopted during interaction analysis for the reason mentioned – and it also can provide very rich descriptions of sequences of interactions with technology (e.g., [Porcheron, Fischer, Reeves, & Sharples, 2018]).

The extent to which the dialogue could be included in the analysis was also limited, due to the fact that only small amounts of any group's dialogue was actually audible in the videos. The *in the wild* nature of the data collection also meant the research had to fit in with the school's schedule and requirements and in this instance, I was not able to test the recording devices in a real setting prior to the study. In the end, there was so much background noise from up to 30 children in the classroom talking at the same time, that it was difficult to discern distinct voices in the recordings. Despite these limitations, the study of the two classrooms revealed just how creative, inventive, and excited students can be when learning about IoT through discovery-based tasks involving a physical computing toolkit. Based on these initial findings, the next study (Chapter 7) was designed to investigate how groups of children learn about critical thinking through using the cubes. However, this time audio recorders were used together with video cameras as a way of collecting and being able to transcribe more of the conversations that took place.

7.6 Summary

This chapter has addressed the question of how interacting with the Magic Cubes can engender embodied interaction strategies that support collaborative discovery of the core IoT concept of sensor-actuator mappings. The analysis of children's interactions demonstrated how they were able to draw upon a diverse repertoire of embodied interaction strategies, that enabled them to readily change control, take control and hand over control when learning together. This study also demonstrated how collaborative learning can be positively influenced by interactions that might otherwise be deemed un-collaborative (e.g., grabbing, pulling away). Moreover, the findings revealed how learning with the Magic Cubes can give rise to playfulness, curiosity and between-group interaction in classroom settings. A further question is how these observed effects can be capitalized on to teach more complex IoT concepts. The next chapter addresses this question. Specifically, Chapter 7 investigates whether and how discovery-based learning with the Magic Cubes can be used to enable children to think critically about the concepts of sensors, the act of sensing, and sensed data.

CHAPTER 8: PROMOTING CRITICAL THINKING ABOUT SENSORS AND SENSING

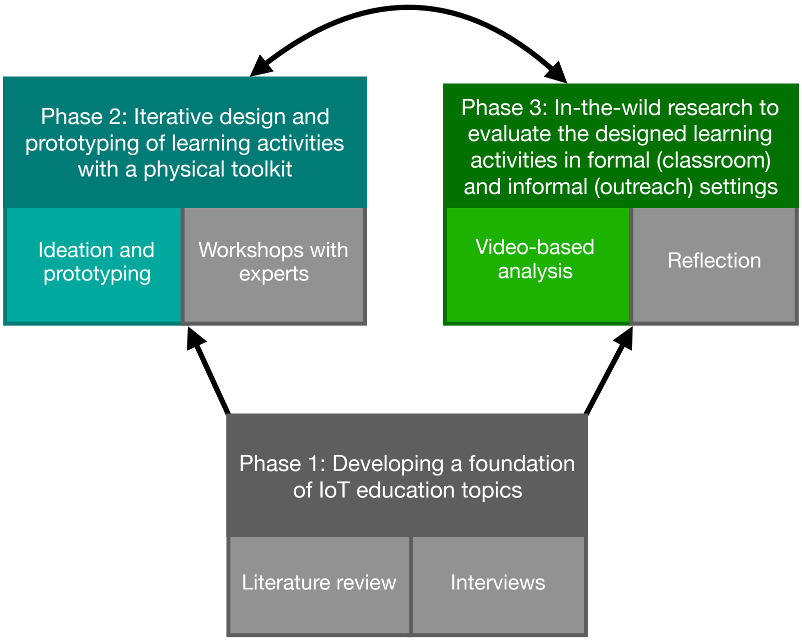


Figure 8.1: This chapter 1) addresses the design of new discovery based activities aimed to promote critical thinking about sensors and sensing, and 2) presents an in the wild study together with a video-based analysis of children completing these activities in their classroom.

The previous chapter demonstrated how the fundamental IoT topics of sensors, actuators and the mappings between them can be first introduced to children in a manner that is playful, embodied and collaborative. It also highlighted how discovering sensor-actuator mappings embedded in a physical toolkit can spark children's curiosity about data. The focus of this chapter is to explore further how playful, embodied and collaborative learning can be capitalized on to promote higher level thinking about aspects of IoT, specifically critical thinking about data. Hence, the next stage of the research was developed to investigate how discovery-based tasks can be designed to enable children to move between learning about what electronic components are, and higher level *critical thinking* about when they might fail and what this means about when to use them. This is considered an important learning outcome because, as demonstrated in Chapter 5, learning to think critically about new technologies and their potential impact is a key motivation for IoT learning.

The topic chosen to teach critical thinking about IoT was the relationship between sensors, sensing and sensor data. Different sensors collect data differently, and some are more accurate, reliable and informative than others. Here, **accuracy** is defined as the extent to which the value detected by a sensor matches a true value, **reliability** is defined by how consistently accurate a sensor is, and by **informative** is meant how useful a sensor value is for understanding a particular phenomenon. For example, a pedometer's accuracy is contingent on how a step is defined, as well as where the pedometer is placed. Equally, how informative a galvanic skin response value depends on the context it is used in. The reason for selecting this topic to teach to school-aged children is that it is central to understanding IoT and yet rarely taught in schools.

This chapter presents the study that was carried out to investigate how the Magic Cubes might be used to promote these types of higher-level thinking. It begins by outlining how the learning activities were designed in conjunction with the Magic Cubes to enable children to move between learning new concepts about sensors and thinking critically about their limitations and context of use. Specifically, the goal was to see whether the children (ages 9-11) could use the Magic Cubes to learn how to evaluate the reliability and accuracy of sensor data, and how informative the data is. The context chosen for this was data they could collect using the Magic Cubes to sense aspects of their bodies and their environment. The findings show how the children built understanding and reflected about sensors, sensing and sensor properties throughout the learning process. The chapter finishes with a discussion about how the sensor properties, the pedagogical materials and the instructors, are all integral to critical thinking, especially through the dovetailing of reflective dialogue and creative interaction.

8.1 Motivation and Research Questions

Critical thinking is becoming an increasingly core component of primary and secondary computing curricula in general (e.g., ["CS4ALL Blueprint Beta," n.d.]) and has been called one of the key skills for the 21st century by leaders in business, education and policy [Partnership for 21st Century Learning, 2019; Trilling & Fadel, 2009]. As discussed in section 2.1, it can be defined as a set of cognitive processes [Lai, 2011] that are used to make informed judgments about information [van Laar, van Deursen, van Dijk, & de Haan, 2017]. Since the 1980s, a wide body of literature has been concerned with defining what specific cognitive processes and skills comprise critical thinking (e.g., [Ennis, 1985; Garrison, 1992; Newman, Johnson, Webb, & Cochrane, 1997]). However, there is much debate about the skills and processes contained within critical thinking, and to what extent they are observable and generalizable beyond a specific context (e.g., [Bailin, Case, Coombs, & Daniels, 1999; Bailin & Siegel, 2002]). Here, based on previous definitions of critical thinking, the analysis is constrained to putative cognitive processes that can be viewed as *useful* to learning about sensors and sensing in context of IoT. Specifically, this study investigates how children can be supported in engaging with the processes of:

(i) **understanding** what sensors measure and how;

(ii) **observing**, **experimenting with** and **analyzing** representations of sensor data to reason about when a sensor may not be working as expected and why, and

(iii) **evaluating** information gathered about sensors in order to reason about how reliable, accurate and how informative they are in general.

Learning to think critically about technology in this way is not straightforward. It is one thing to be taught what high-level technology concepts like reliability and accuracy are. It is another to be able to put them into practice and operationalize them for different problem spaces. Teaching critical thinking requires considering how learning tasks can be developed to foster curiosity, experimentation, and importantly, "stepping out" [Ackermann, 1996] from a situated activity in order to analyze and reflect on what is being learned. To investigate how this type of critical thinking could be facilitated when learning about IoT in a classroom setting, the following research questions were addressed in the study:

> ***RQ 8.1:*** *Can discovery-based tasks enable children to think critically about sensors, sensing and sensor data in a classroom context?*
> ***RQ 8.2:*** *What are the components of critical thinking that occur during discovery-based learning?*
> ***RQ 8.3:*** *What mechanisms trigger critical thinking about IoT concepts?*

8.2 Session Design

An important part of considering teaching about critical thinking in context, is to determine how to provide appropriate guidance during the learning process, and how to support students in verbally reflecting on learning activities with the help of peer and teacher support structures. With this in mind, the session design aimed to provide open-ended tasks together with appropriate guidance, to promote collaboration between peers, and to enable flexible support from instructors. Specifically, the pedagogical framing for the proposed study was to adopt the following 4 steps:

1. *Introduce sensors and sensing.* Verbally define *physical sensors and sensing* at the beginning of the class, together with examples, to introduce the children to the concepts that they would be using during the discovery activities.
2. *Frame the exploration of data collection in relation to the self and the environment.* Enable the children to engage in collecting and visualizing personal and environmental data using sensors in an open-ended way.
3. *Encourage verbalization and reflection throughout:* Get the children to work in pairs/groups to enable collaborative learning to happen throughout the session, by providing multiple opportunities for them to show and tell, test their hypotheses and explain their discoveries to one another.
4. *Engage the children in a reflective discussion:* Prompt the children to reflect on their experiences with exploring the sensors, by engaging them in a reflective discussion supported by the instructor.

Next, the tasks the children were asked to work through are presented.

8.2.1 Sensors used

A number of different sensors were used with the Magic Cubes for this study. Three of them allowed the children to explore their own personal data; these were (i) a **galvanic skin response (GSR) sensor** - which measured the resistance of the skin, an indicator of emotional arousal, (ii) a **pedometer -** which measured aggregate step count using an accelerometer-based algorithm, and (iii) a **pulse sensor** - which measured the amount of light reflected from the fingertip to infer when a heartbeat occurred. Two other sensors were also provided to enable the children to explore data from their environment. These were (iv) a **light sensor** – which measured the amount of light in the environment and (v) a **temperature sensor** – which measured the temperature in degrees Celsius. An assumption when choosing these sensors was that they would enable the children to explore things that would be of interest to them – including aspects of their own bodies, and data about their classroom environment. It was also assumed that gathering sensor data about things that they had some prior knowledge about (e.g., how fast their heart beats or how hot it is in the room) would enable them to more readily reflect on the accuracy and reliability of the data sensed by the Magic Cubes. Figure 8.2 and Table 8.1 describe in more detail the sensors used, together with how the ambiguities and inaccuracies of the sensors were capitalized on for the learning activities.

8.2.2 Visualizations used

In contrast to the Magic Cubes tasks in the previous study, reported in Chapter 6, the data from the sensors in this study was represented in this study in a more concrete way. This was because the goal of this study was to enable the children to reflect on how the data collected by the sensors changes in different contexts and under different conditions. Therefore, it was considered important that the children be able to easily understand the data that was sensed by the sensors, rather than to focus on understanding abstract sensor-actuator mappings. For these reasons, for four of the sensors (all but the pulse sensor), the cubes were programmed to provide a real-time numeric reading by printing the numbers on the embedded LED matrix – an example of which is visible on the temperature sensor image in Figure 8.2. When the full number did not fit on the LED matrix, it was scrolled on the LED matrix. The pulse sensor that was used was sensitive to changes in light, and due to this it often sensed a false pulse; this meant that the heart rate in beats per minute was consistently inaccurate, even when tested before the study. It was considered that providing the children with a numeric representation of heart rate that was so consistently wrong would be counterproductive. Instead of a numeric reading, therefore a symbolic, real-time beating heart representation was used for the pulse sensor. This is visible on the pulse sensor image in Figure 8.2. This choice of visualizations used on the cubes was intended to be easy to read and simple to make inferences from and compare with other readings.

8.2.3 Field journals to guide interactions in situ

Similar, to the previous study, the discovery-based learning activities that the children were asked to carry out were intentionally open-ended. However, in the previous study (Chapter 7) it was found that when only provided with verbal guidance, the children often waited for the instructor to help them out when they got stuck. This could take a long time when the instructors were busy with other groups. For teaching critical thinking it was decided that it was also important to provide scaffolding in the form of written suggestions and guidance, that would encourage the children to reflect on the activities that they were carrying out throughout the learning process. This is because 'pure discovery' without appropriate guidance has been shown to make this type of reflection more difficult [Alfieri et al., 2011; Mayer, 2004]. For these reasons, it was decided to provide each child in this study with a *field journal*. The field journals were designed as a guide for the children's interactions in situ. They comprised a booklet of activity sheets with suggestions for what to explore for each sensor, and questions to trigger reflection about the sensor properties and functionality (see Appendix B for the full booklet). They included three types of guidance: **getting started**, **suggestions for what to explore** and **reflective questions.** Figure 8.3 shows an annotated extract from the field journal, with examples of each type of guidance.

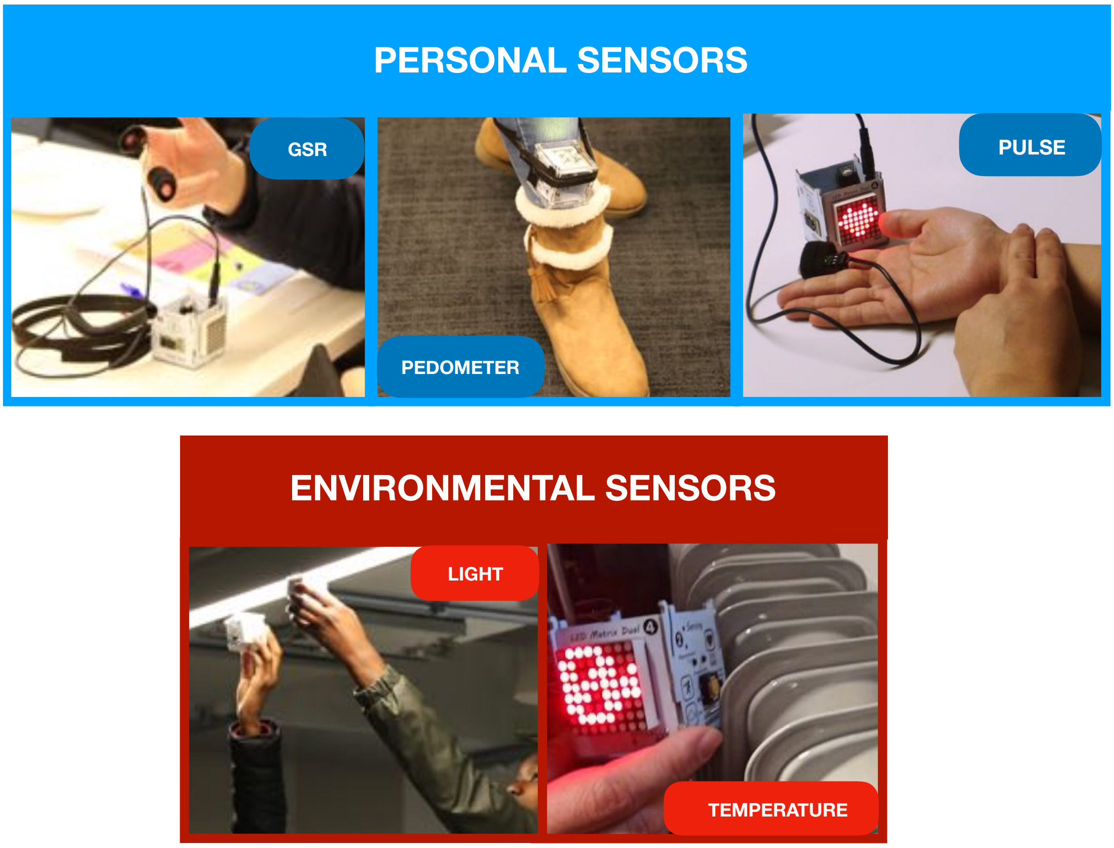


Figure 8.2: The five pulse sensors used for this study. Three of the sensors measured personal data, specifically: (top-left) the Galvanic Skin Response (GSR) sensor which was used by placing two fingers on electrodes situated in finger gloves, (top-middle) the pedometer, which was used by strapping the cube to the foot, wrist or other part of the body using a Velcro strap, (top-right) the pulse sensor, which was used by placing one finger on a sensor situated inside a finger glove. Two of the sensors measured data in the environment, specifically: (bottom-left) the light sensor and (bottom-right) the temperature sensor. Both of the environmental sensors are embedded inside the cube.

Table 8.1: This table describes the sensors used for the discovery task. It expands on what the sensors measure and describes the sensor properties that it was hoped the children would reflect on.

Personal Sensors

Galvanic Skin Response (GSR):

The GSR sensor is an external sensor that was plugged into the Magic Cubes using a headphone jack. To use it, the children had to place two fingers inside the two finger gloves of the GSR sensor, and position their fingertips on the electrodes inside the gloves. Changes in GSR are linked to activity in the sympathetic nervous system, which is beyond conscious control. When emotional arousal—either positive or negative—occurs, sweat gland activity, controlled by the sympathetic nervous system, increases. The increase in sweat increases how conductive the skin is, and simultaneously decreases the resistance of the skin. The resistance **decreases** with emotional arousal, therefore, the sensor value **drops** when emotional arousal, such as stress, occurs. The LED matrix of the cube was programmed to display the numeric value of the resistance detected on the skin.

Pedometer:

The pedometer was created by appropriating the accelerometer embedded in the Magic Cubes. Specifically, the accelerometer was programmed to measure how much acceleration was detected in its x, y and z axes, and check whether the acceleration from all three axes was in the range typical of a step. If it was, a step count variable increased by 1. The LED matrix on the cube was programmed to display the total number of steps detected. A Velcro strap was provided with the pedometer to enable the children to strap the cube to their foot, wrist, or other part of the body. Testing the code prior to the study revealed that this pedometer was able to measure a child's steps with high accuracy, especially when placed on the foot. However, the accuracy varied depending on the placement of the pedometer, how light or heavy the steps were, and when the type of movement by the wearer of the pedometer cube was atypical of a step – for example running or dancing.

(iii) **Pulse:**

The pulse sensor was an external sensor that was plugged into the Magic Cubes using a headphone jack. To use it, the children had to place one finger inside the finger glove of the pulse sensor. The sensor consists of an LED light and a reflective optical sensor. It works by shining the LED light into the fingertip, and measuring how much of the light is reflected back using the optical sensor. This is able to measure pulse, because the amount of light that is reflected back changes with the flow of blood after a heart beat. The pulse sensor that was used, however, was sensitive to the amount of light around it, and would sometimes give a false pulse signal, for example if the finger was placed too lightly on the sensor. Moving the wire to which the sensor was attached could also produce an inaccurate signal, thereby 'detecting' a heart beat even when the finger was not placed on the sensor. This was hoped to elicit reflection about sensor accuracy. However, because of this, measuring a heart rate (in beats per minute) as opposed to a pulse in real time was considered to be too inaccurate. Therefore for the pulse sensor, a real time symbolic visualization of a beating heart was displayed on the cube's LED matrix, as opposed to a numeric visualization of the heart rate.

Environmental Sensors

(iv) **Light:**

The light sensor was embedded on one of the external sides of the cube. It measured the level of light detected in lux units. The LED matrix was programmed to display the numeric reading of the light level in lux. Because the light sensor is small and positioned on one side of the cube, small changes in the position of the cube (e.g., in what direction the cube is tilted in relation to a light source) make a big difference to the light level detected. This was one of the things it was hoped the children would reflect on.

(v) **Temperature:**

The temperature sensor was embedded on one of the external sides of the cube. It measured the temperature in degrees Celsius. The LED matrix was programmed to display the numeric reading of the temperature. The temperature sensor reading changes gradually, rather than immediately stabilizing. This was one of the things it was hoped that the children would reflect on.

Getting started

For each sensor, the field journal included one or two questions intended to help the children get started with exploring the data collected from the sensor, and to hint at how the data from that sensor could sometimes be unexpected or ambiguous. For example, a GSR reading takes several seconds to change, which can be difficult to grasp, when assuming the outcome of an action to be immediate. To enable the children to experience this, the field journal asks them to "take a deep, sharp breath in" and observe how long the sensor reading takes to change. This enables them to see a baseline of how rapidly and how much the reading changes. For the pedometer, the journal asks the children to walk around, count the number of steps they take, and compare this to the number on the pedometer. This enables them to test how accurate and reliable the sensor is when walking normally.

Suggestions for what to explore

For each sensor, the journal also included open-ended suggestions to encourage the children to explore the sensor more creatively. For example, the temperature sensor activity asks the children to try to get the cubes to display the hottest and coldest temperature possible, by using their existing knowledge of temperature differences in materials and areas of the classroom. The suggestions also prompted the children to try "tricking" the sensors. For example, the pulse sensor activity asks the children to figure out how they can get the pulse sensor to 'think' their heart is beating very quickly.

Reflective questions

The reflective questions in the journal were aimed at getting the children to discuss and write down what they observed, as a way of encouraging them to make explicit the process of hypothesis testing and coming to conclusions. For example, when the suggestions for what to explore asked the children to try "tricking" the sensors, this was followed by reflective questions – e.g., "write down what you tried and if it worked."

Field Journal Extract (Exploring the Pulse Sensor Activity)

Feel your own heartbeat by putting your hand on your heart, wrist or neck. Once you feel, it, put your fingertip on the pulse sensor. Try to put your fingertip on the sensor in a way that your the beating heart on the cube matches your heartbeat.

Try pressing your finger down hard on the sensor. Then try putting it on the sensor only very lightly. What worked better?

Putting fingertip hard on the sensor   Putting fingertip lightly on the sensor

Can you try tricking the pulse sensor into thinking your heart is beating much faster than it really is? Write down what you tried and if it worked.

Key:	Getting started	Suggestions for what to explore	Reflective questions

Figure 8.3: An extract from the "Exploring the Pulse Sensor" field journal activity. The text highlighted in red relates to getting started guidance, the text highlighted in blue relates to suggestions for what to explore, and the text highlighted in green relates to reflective questions.

8.3 School Context and Participants

A one-off session was designed to be run in 5 different classrooms. Running the same session in five different classroom settings allowed us to see whether the findings would carry over to different classrooms. The 5 sessions were conducted in different classrooms at three different mixed-gender, mainstream schools in England. The number of participants in each class ranged between 12 and 24 children. Four of the sessions were held in Year 6 classes (with children aged 10-11) and one was held in a Year 5 class (with children aged 9-10). A total of 86 children participated in the study. Table 8.2 provides specific details about the participants in each school/classroom, and the school contexts are elaborated in more detail below.

Table 8.2: The number and age of the children in each classroom.

School/Class		School Year	Ages of Students	Number of Students
1		5	9-10	24
2		6	10-11	15
3	Class 1	6	10-11	18
	Class 2	6	10-11	17
	Class 3	6	10-11	12

The participating schools were recruited through a number of public engagement events where the Magic Cubes were showcased. The events were all concerned with showcasing students' computing achievements across London as well as introducing teachers and children to new technologies for supporting computing education. Thus, all of the schools had a demonstrable prior interest in expanding their computing provision, and were working towards integrating best practice approaches for computing into their curriculum. However, within these year groups, none of the schools taught IoT to their students specifically, and none had integrated lessons about critical thinking about sensors and sensing prior to this study.

School 1 was a mixed gender community primary school with a total number of approximately 500 pupils, between the ages of 2 and 11 and an average class size of 29. The school is situated in a city context, in an inner borough of London, with 35.7%

of pupils eligible for free school meals. A total of one teacher and 24 children, who were all in Year 5, participated in the study; the session took place in their typical classroom and class group.

School 2 was a mixed gender community primary school with a total number of approximately 450 pupils between the ages of 3 and 11, and an average class size of 30. The school is situated in a city context, in an inner borough of London, with 31% of pupils eligible for free school meals. A total of one teacher and 15 children, all of whom were in Year 6, participated in the study. The session took place as part of their school's enrichment provision, and so, the children were chosen to participate in the session by the school on the basis of their interest in computing. Therefore, the participating children were not in their typical class formation during the session; however, they all knew each other from other group work in their school.

School 3 was a mixed gender, primary academy with a total number of approximately 450 pupils between the ages of 3 and 11 and an average class size of 27. The school is situated in a city context in an outer borough of London, with 22.9 % of pupils eligible for free school meals. A total of two teachers and 47 children participated in the study. Each of the three sessions that was run took place in the children's typical classroom and class group. Due to the proximity of the sessions to the school's summer holidays, and other end of school year events taking place at the same time, a number of absences were recorded in each session.

8.4 Procedure

The sessions were planned to last for 90 minutes. The amount of time that the sessions lasted varied depending on the school – for example, in school 3 class 1, the session time was cut short to 60 minutes because of a last minute, school-wide assembly. It was considered that a session of 60-90 minutes would be sufficient to introduce the concept of sensing, to enable the children to put this conceptual definition into practice by exploring the Magic Cubes and to engage them in reflective discussion. Despite this, the children were able to get through the core activities that were planned for the session. In practice, the sessions were broken down as follows. The researcher first spent 10-15 minutes introducing the Magic Cubes, and verbally explaining concepts of sensors and sensing to the class. Next, for each of the five sensors, the students were given 7-10 minutes to explore how the sensor worked and to experiment with it, with the help of the field journal. The rest of the time was spent on a reflective discussion after the discovery task. Where there was time left over after these phases, the children were given another task, where they were asked to come up with a new invention that they could make with a sensor of their choice, or to program different data visualizations onto the cube. However, because most of the children did not get to this stage due to the time constraints of the session, this last phase was not analyzed.

Before the session, the teachers informed the children of the purposes of the study, which was to investigate how the Magic Cubes toolkit works in real classrooms. The children were also given a consent form for their parents to sign. At the beginning of the session, the researcher asked for the children's consent to be video and audio recorded; all consented. For each session, a teacher from the school was present, as well as the researcher, and up to two additional research assistants (depending on their availability and the class size). The role of the researcher and the research assistants was to facilitate the activities during the sessions and guide the children through the tasks. Although the teachers were encouraged by the researcher to take an active role in facilitating the sessions, in two of the classrooms (School 1 and 2), they chose to take a backseat and instead mainly observed the session, while the researcher led it. The children were asked to get into pairs, and chose their own partners, although in some instances the teachers changed the children's preferred pairs when s/he expected the pair to be disruptive.

8.5 Data Collection and Analysis

8.5.1 Data collection

For each session, video cameras and audio recorders were placed throughout the classroom. This was to enable continuous audiovisual data of the children's interactions and dialogue when carrying out the tasks to be recorded, and hopefully to capture their individual conversations. The audio recorders were placed on each desk; the video cameras were distributed so as to record both close shots of children sitting at their desks, and an overview of the classroom that captured the instructors (i.e., the teacher, researcher and research assistants) and the children's interactions when not at their desks. The children were also asked to use and fill out their field journals during the session. In addition, the researcher wrote field notes during the sessions.

8.5.2 Data analysis

Compared with the previous study, most of the conversations were audible and able to be transcribed. The children's writings in the field journals and the researcher's field notes were also used as part of the analysis. A mixed methods qualitative approach, which capitalized on the foundations of Interaction Analysis, was used to analyze the audio and visual data. The main emphasis was on analyzing the children's physical interactions and dialogue, with both their peers and the instructors.

First, the video and audio recordings were combined and iteratively viewed and annotated (total ~1100 minutes of footage across all the cameras) to create content logs of the sessions. The dataset was then analyzed in terms of envisioned critical thinking outcomes. Specifically, the envisioned critical thinking outcomes were: *(i) extrapolating what the sensor measures and how*, *(ii) being able to reason about why and when the sensor may not be working as expected*, and *(iii) being able to reason about the accuracy, reliability and limitations of sensors in general*. It was assumed that each of these envisioned outcomes involves distinct putative cognitive processes, which are considered core aspects of critical thinking as outlined in Chapter 2. To facilitate the analysis, a classification system (see Table 8.3) was used that mapped the three envisioned outcomes with: the putative cognitive processes involved; a description of the type of thinking hoped the children would engage in; and a question that was used to guide the analysis. The aim of using this classification system was to provide a lens through which to label how the different cognitive processes that are assumed to underlie critical thinking, took place during the sessions. Based on this classification system, meaningful events were identified that related to the envisioned critical thinking outcomes. A meaningful event could be, for example, a pair of children observing a counterintuitive property of a sensor, and using this to reflect on what the sensor measured and how. The meaningful events that were identified were transcribed in terms of the dialogue between the children, together with annotations about what the children were exploring at the time of the event, and how they were using their bodies (for example,

Table 8.3: The classification system used for this study, based on putative cognitive processes involved in critical thinking.

Envisioned outcome	**Putative cognitive processes involved**	**Description**	**Question driving analysis**
Extrapolate **what** the sensor actually measures and **how**	**understand, describe**	Although some sensors measure what their name indicates, others do not. For example the pedometer measures movement (e.g., using an accelerometer). Likewise, the GSR sensor measures skin resistance. Perceiving this relationship is viewed as corresponding to the cognitive processes of understanding and describing.	Do activities related to understanding a sensor, for example recognizing and localizing the sensor, lead the pairs to infer what it measures and be able to describe relationships/mappings between actions (e.g., telling a lie) and the sensor reading (e.g., the GSR reading decreasing)?
Be able to reason about **why** and **when** the sensor may not be working as expected	**apply understanding, experiment, analyze, infer**	We examined whether the children could reason why a sensor might not be working, by applying their understanding of sensor functionality. This is viewed as mapping to the processes of applying understanding, experimenting, analysing and inferring. For example, applying the knowledge that a GSR sensor measures moisture might help the children analyse that if the sensor is wet, the reading is likely not accurate.	Does applying the knowledge of what a sensor measures allow children to infer and analyse when it might become inaccurate, uninformative or unreliable?
Be able to reason about the **accuracy, reliability and limitations** of sensors **in general**	**evaluate, judge, decide**	It is one thing to analyse how a specific sensor works in practice, but another to extrapolate this when reflecting on sensors in general. For this learning outcome, the goal was to investigate how and when children explicitly discuss and evaluate the factors that impact how accurate, reliable and informative sensor data is overall.	Do pairs of children do this when discovering the sensors together, or is facilitation required from instruction to promote explicit discussion?

whether they were reaching towards the light, jumping, dancing or securing a sensor to a part of their body). Through this process, the analysis led to descriptive findings about the contexts in which the assumed cognitive processes occurred, and the extent to which the children were able to engage with each of the envisioned outcomes during the session.

8.6 Findings

Overall, the findings showed that the children were able to move between understanding how the sensors worked and reflecting on their properties, while carrying out the discovery-based tasks, where they collected personal data and came up with ways of testing their hypotheses about how accurate and reliable the data was. This was evidenced by many instances of them verbally reflecting about data values that were unexpected, and of hypothesizing why the sensor data was not always correct. The open-ended nature of the tasks engendered many playful, creative and collaborative interactions amongst the pairs. However, it was found that the children did not spontaneously talk about the concepts of sensor reliability and accuracy explicitly during the discovery tasks. They needed to be prompted by the teacher/researchers to try to generalize from their specific experiences at the end of the class, during the discussion phase of the session. In some ways, this is to be expected, given that it is something they are not used to talking about. However, the fact that some were able to talk more generally about the concepts when prompted suggested that the hands-on approach adopted here was effective at encouraging the children begin to engage in aspects of critical thinking. The next sections detail the critical thinking processes that took place as the children engaged in the learning activities. The findings below are organized in terms of the framework presented in Table 8.3, in terms of the 3 envisioned outcomes, and the specific research questions asked to drive the analysis.

8.6.1 Envisioned outcome: extrapolate *what* the sensor actually measures and *how*

The first question addressed was whether exploring the data gathered by the sensors would enable the children to **understand** what the sensor measures and how it does this. Below, I demonstrate the ways in which the children learned to localize and use the sensors, and extrapolate what they measure from their description (e.g., that the 'pulse sensor' measures reflected light, and that the 'galvanic skin response sensor' measures resistance as a function of moisture).

Localizing and learning to use the sensors.

At the beginning of interacting with each sensor, the children were faced with the challenges of localizing the sensors, figuring out how to position them on the body, and understanding what the values and symbols on the LED matrix meant. It was observed during all of the sessions, that when receiving a new sensor to experiment with, a majority of the children dived in to exploring how it worked, without reading the *getting started* suggestions provided in the field journal. Instead it was found that during the process of localizing and learning to use the sensors, the children flexibly mixed experimenting with the sensors in their pairs, with utilizing the variety of support structures available around the classroom.

For example, in order to understand how the light sensor worked, a challenge that the children faced was figuring out that it was a small, physical component, rather than the whole cube itself, and finding where on the cube it was embedded. Because the light sensor is so small, finding it was not immediately obvious. Although the field journal asked the children to try to find the light sensor as a first step, only a minority of them read this instruction when getting started; instead, many of the children started experimenting with the cube as soon as they received it – especially trying to find how high and low they could get the light sensor value displayed on the LED matrix of the cube. However, even without intentionally looking for the sensor, it was found that they were able to achieve the intended outcome of localizing it. This was supported through watching others around the classroom, and asking their peers for help. The following vignette exemplifies these processes.

A pair had figured out where the light sensor component was positioned on the cube, and had the idea of putting the light sensor on the cube directly under a projector light. They exclaimed that their sensor reading was '986', which was much higher than any other pair in the classroom had managed to get before. Another pair, observing this, mimicked their strategy of placing the cube under the projector, but was unable to get the sensor reading as high, and asked the first pair for help. A member of the first pair then demonstrated how to tilt the side of the cube on which the light sensor was located so as to maximize the value, as illustrated below:[3]

> *C1: Robbie, how did you get 986? […]*
> *C2: I just put it all the way in [the projector] for a while. Like all the way. [pause; Robbie comes over and repositions the cube] Maybe that'll help out guys. That'll help.* ***If you plug it in with that sensor [pointing to the side of the cube containing the light sensor], it'll help… Let's try it this way.***
> *C1: [Positions the cube as C1 suggests] Yayy, Robbie, 992!*
> *C2: You're welcome! [C2 leaves to join his own partner]*

Here, C2 describes where the light sensor is embedded to the other pair, and suggests how they can position the cube so as to increase the value displayed on the LED

[3] Bold segments within the vignettes highlight when and how the interaction supported reflection and critical thinking; all names have been changed.

matrix. By observing where he points and copying C2's strategy, C1 learns that to maximise the light level value, she needs to take into account the location of the sensor on the cube.

For the externally attached sensors – that is, the GSR and the pulse – the finger gloves made it evident where the sensors were located. However, in order to learn how to use them, the children first had to figure out how to place their fingers inside the gloves in order to elicit an accurate sensor reading, specifically by placing their fingertips directly on the electronic components, and experimenting with how much pressure to put on the sensors. For the GSR sensor, the observation notes taken during the sessions showed that in each class, some pairs of the children were observed to place the electrodes on their fingernails rather than on their fingertips, or had each partner in a pair placing one finger in a finger glove simultaneously. This meant that the sensor would not be able to measure the change in resistance from sweat gland activity. It was found that as the sessions progressed, the class teacher and the researcher team began to preempt these issues, by explaining to the children how to correctly place electrodes on their fingertips as soon as they handed the children the GSR sensor, for example, "*so put them both on the same hand, and yeah... just make sure the metal bit is touching your fingertip.*" It was also found that the children prompted each other to engage with the field journals when they did not understand how to use a specific sensor. The following example shows them trying to measure their pulse but being uncertain where to place the sensor:

> *C1: Does it go on your middle finger?*
> *C2:* ***Read what it says on the sheet!***
> *C1: Um ok – [reads] 'Hint: keep your finger on the top of the green LED light, you might have to…' LED light.. Oh that LED light. [reads] 'you might have to experiment with how hard or how gently you place your finger on the sensor.' I think it's that one.*

In sum, it was found that most of the children immediately dived into exploring the sensors, without referring to the field journals to guide their initial exploration. However, the processes of localizing the sensors and learning how to use them were flexibly mediated by a number of support structures in the situated learning environment – including peer and instructor guidance, and the field journals.

Understanding what the sensor measures

A second key challenge that the children faced in the initial stage of understanding the sensors was learning about what the sensors measure and how to interpret the visualizations. It was assumed that this would be especially difficult for the three personal sensors that were used – the GSR, pulse and the pedometer – all of which measure indirect indicators of a phenomenon, rather than the phenomenon itself. Specifically, the GSR sensor measures the resistance of the skin as an indicator of emotional arousal; the pulse sensor measures the amount of light reflected on the fingertip as an indicator that the heart has beaten; and the pedometer measures whether the movement of the cube itself is in a range that is likely to indicate that a step was taken, assuming the cube is strapped to the body. The analysis focused whether and how they verbally reflected on the distinctions between the sensor description and what the sensor actually measured.

One of the ways in which the children were found to engage in this kind of reflection was through the questions raised by the instructors (the research team and teachers), who walked around the classroom to check in on the children's progress. For example, the researcher (R) noticed that a pair who had said they were done with the pulse sensor had not filled out the section in the field journal that was about tricking the sensor. The researcher then asked the pair how far they had gotten with this part of the task:

> *R: Have you tried tricking it yet?*
> *C1: How do you trick it?*
> *R: So um, [pause] you have to figure out when it doesn't work. [...] it's not on your finger and it's still kind of giving a heartbeat, right?*
> *C1: Yeah*
> *R:* ***why do you think that is?***
> *C1:* ***(confidently) The table. Cause we're like jiggling the table – and going like that --***
> *R: --* ***Yeah. So what do you think it's actually measuring?***
> *C1:* ***Like movement?***

Here, the researcher is first clarifying what is meant by "tricking" the sensor, and next asking the child to make a hypothesis as to why the LED matrix of the cube is indicating that a pulse has been detected, when the fingertip is not on the sensor. In this example, C1 was not correct in saying that the pulse sensor is measuring movement; however, this instance led the pair to start hypothesizing about other ways to "trick" the sensor. Specifically, after this instance, the video showed them experimenting with the sensor in other ways, for example by tapping it, which also led the sensor to detect a false 'pulse'. This pair later participated in the classroom discussion, where they discussed how the pulse sensor reflects light. This example demonstrates how the instructor was able to lightly promote reflection about what the sensor measures and how, by asking the children "why?" which led the children to new ways of thinking about the sensors – specifically, reflecting on how they work, and what they measure.

It was found that for all of the sensors except the GSR sensor, the children were seen to spend very little time reflecting on how the visualizations mapped onto the phenomena being measured. The way the data was represented seemed to be easy to understand – for example, the light level represented on the LED matrix increased in brighter places, and the LED matrix flashed a heart when a heart beat was detected with the pulse sensor. However, for the GSR sensor, most of the children found the directionality of the change in the values confusing. This was because the sensor was measuring resistance, a value that *decreases* with emotional arousal (e.g., stress when telling a lie) – which is counterintuitive if assuming that telling a lie makes the sensor value rise. It was observed that when interacting with the GSR, they spent much time trying to understand what increased and decreased values meant – for example, by asking each other repeatedly whether the GSR value goes up or down when telling a lie.

Moreover, when some of the children first placed the GSR sensor on their fingertips, the value was as low as 0 or 1. This happened when they had wet fingertips, or when the sensor was wet from someone who had used it before. In these instances, there was no room for the sensor value to drop further, which impeded exploration of the data. However, it was found that experiencing this issue sometimes had the positive effect of enabling the children to reason about how the GSR sensor might work and what it might measure. For example, one child reflected, *"I asked everyone everything, and I got 0!"*. After being asked why this happened by the instructor, he replied that, *"it was wet when I put it on!",* which suggests that he had reasoned that moisture played a part in the GSR data.

For the pedometer, it was found that the children were able to make a distinction between the measurement of movement and the measurement of the more abstract concepts of steps – and moreover, reflect on why this mattered in context of accuracy. For example, while having the pedometer strapped to her wrist, a student noticed that it was adding steps when she moved her hand, and later reflected on how an everyday pedometer might work in practice, for example,

"you see like, when you wear those thingies like – the Fitbits and stuff – it's on your wrist. […] I think ***it's like checking like when you move your hands around****. I think* ***it's going to the rhythm of that, not actually [your step].****"*

This inference demonstrates her making a distinction between the concept of movement, and the more abstract idea of steps.

8.6.2 Envisioned outcome: reason about *why* and *when* the sensor may not be working as expected

The second intended outcome of the session was for the children to reason about when and why the sensor may not be working as initially expected. As described in Section 8.2, the sensors that were used were not always reliable, accurate or informative. For example, the pulse sensor is prone to being inaccurate, especially when the wire is moved, or when the finger is placed too lightly on the sensor. How informative the sensor was also varied depending on the context of use – for instance, the GSR sensor is informative as a way of measuring changes in emotional arousal, but not as a lie detector *per se*. To address whether and how the children engaged with these issues, the analysis focused on how their experimentation with the sensors challenged their assumptions, and in what ways they verbally reflected about this. It was found that through the process of experimenting with the different sensors, and applying their knowledge of what the sensor measured, the children were able to reflect on when the visualizations on the Magic Cubes did not match up to the real data, and why.

Reflecting through embodied interaction

The guidance provided in the field journals for the pedometer asked the children to experiment with the accuracy of the step count when the pedometer was attached to different parts of the body, as well as to figure out how they could trick the sensor to "think [they] took more steps than [they] actually did." When exploring the pedometer, the children were seen to experiment with a variety of embodied interactions with the cube, like shaking the cube, dancing with the cube, jumping around or walking without moving their arms. It was found that by doing this, they were able to begin to observe and analyse how the position in which they placed the cube on their body, as well as the type of movements they enacted, influenced the accuracy of the step count. For example, after attaching the pedometer cube to her wrist, and walking without moving her hands, a girl reflected:

> *'**let's say the pedometer was on my wrist**, and over there [points to a narrow space between two desks], when I tried to get through it I couldn't move my hand back [...] and I think when I moved my hand it counted the steps... **And I didn't move my hand so it didn't count that as steps**."*

Reflecting on unexpected sensor behaviors

Another way the children reflected on sensor accuracy and reliability was through observing unexpected sensor behaviors. This happened most frequently with the GSR sensor. One of the *suggestions for exploration* posed in the field journal for the GSR was to use it as a lie detector – by asking each other to tell lies and seeing if the value displayed on the LED matrix would rise or fall. This was found to be the children's favorite use case for the sensor, and across all sessions and pairs, the children were observed to spend the majority of the time allotted for the GSR sensor by testing out the GSR's lie-detecting abilities. Specifically, they spent time asking each other playful questions and guessing if they were lying by checking if the GSR value displayed on the LED matrix of the cube changed.

When using the GSR in this way, many of the children initially assumed that the sensor would be able to tell when someone was lying in all instances. However, experimenting with telling different types of lies and truths while wearing the GSR sensor enabled them to observe that the sensor was not consistently able to catch them when they were lying. Specifically, the children were observed to ask each other a range of questions, including fairly innocuous ones (e.g., *"do you like chocolate?"*, *"have you ever teleported?"*) and more stressful ones (e.g., *"do you have a crush on someone in this class?")*. The different kinds of questions triggered different levels of emotional arousal in the one answering, which were not always tied to lying or telling the truth. Sometimes, answering a question caused the GSR value to fall to as low as 1 or 0, while other times it stayed the same or increased slightly. For example, when one of the children lied about having teleported, the GSR value neither decreased nor increased, which, under the assumption that the value would drop when a lie was told, would indicate that the child had indeed teleported. In another instance, when asked whether she had a crush in school, one of the children said yes. Because this was a stressful question, the GSR value dropped quickly from 140 to 47, prompting her partner to accuse her of lying:

> *C1: Do you actually? [pause; watching the sensor value, which decreases] You're lying!*
> *C2: I'm not. It just went to 47… I'm not!*

These types of instances were able to challenge the children's assumption of the GSR as an accurate lie detector, as well as enable them to question how informative the GSR sensor was when used in this way. For example, one of the children asked the instructor, *"what if you don't get stressed when you're asked a question? People don't always get stressed!"*

It was found that reflecting on unexpected sensor behaviors conversely also helped the children reflect on the first envisioned outcome – that is, understanding what the sensor measures and how. For example, a pair had been trying for several minutes to elicit a sensor response by asking each other to tell white lies (for example, by asking "*do you like pizza?*"), but noticed that the GSR sensor value on the LED matrix was not changing as they had expected. The class teacher stepped in to point out the relationship between stress and moisture on the skin, as opposed to lying and moisture on the skin:

> *T: You know what? Why I don't think it works with that as much is because* ***you're just saying a lie but you're not really feeling that stressed, whereas the reason it's doing it is because it's measuring moisture****. But actually if somebody asked you something and you were quite under pressure and you had to lie, you'd feel more stressed than if you were telling the truth. Do you see what I mean?*
> *C1: Yeah. Ok! [...]* ***what's a question she can get stressed on though?***
> *T:* ***What Kira, you don't like Harry Potter? [in a shocked voice]***
> *C1: [sensor reading drops] 227! … It's getting higher then lower, then lower, then lower and then higher. You're at two hundred… 257. [pause]* ***Ok. Are you scared? Of me?***
> ***C2: No [laughs]***
> ***C1: It went down, you are scared of me!***

This vignette shows how after the students experience unexpected behaviour of the sensor not catching them out on the lie, the teacher (T) intervenes and clarifies the functionality of the GSR sensor (which maps to the first envisioned outcome of understanding what the sensor measures and how). She gives an example of how to elicit a stress response in the skin. The children immediately notice the sensor reading dropping, and next, are observed rapidly applying the new strategy within their pair. Specifically, C1 asks if C2 is scared of her, and the sensor reading changes further.

These types of unexpected sensor behaviours were seen to trigger reflection about the pulse sensor and pedometer as well – for example, observing the inaccuracy of the pulse sensor when the heart animation flashed when moving the finger (e.g., "*every time I put my finger on it just flashes*"), or how the pedometer added a number of extra steps when it was picked up off the floor (e.g., "*I took it up with me to the table, and the number went up to 58!*").

However, much less reflection and verbal reasoning was found to occur for the light and temperature sensors. For the light and temperature sensor, the children were seen to spend much time reasoning about the material properties of objects, for example, discussing why a rubber spatula is warmer than a metal table leg, or why pointing a cube towards the indoor light shows a lower value than pointing a cube towards the sun. There were much fewer observed instances of them reasoning about the sensor data itself. The lack of explicit reasoning about the sensor properties may have been because the light and temperature sensors are relatively easy to understand and use—that is, they measure what their name indicates, and while they were not always accurate, they did not present any obvious unexpected behaviors that the children could tie back to observed or experienced phenomena. For example, a light value in lux is difficult to relate to an exact light level in the real world, and so is a temperature value. This afforded focusing mostly on what was to be measured, rather than the device used for measuring.

8.6.3 Envisioned outcome: reason about the accuracy, reliability and limitations of sensors *in general*

The third question addressed was whether the acts of exploring and reasoning about the sensors through the discovery-based activities would enable the children to reflect about the accuracy, reliability and limitations of sensors and sensor data in general. Throughout the sessions no instances were found of the children talking about these explicitly, during the discovery based activities. However, when explicitly asked about them during the reflective discussion phase of the session, it was found that some of the children were able to reflect on these high level topics together as a group, for example:

> *R: So what does that tell you about sensors? Are they accurate?*
> *C1: They're very accurate*
> *C2: They're not very accurate [shaking head].*
> *R: So what does it depend on?*
> *C3:* ***They're accurate, but it's easy to trick them so you have to be careful how you use them****. So if you're like, if you're going too fast, then it won't detect it, if you're moving your legs too fast, it won't count the right amount of steps so you have to be careful how you actually use them.*

Here, C3 builds on her classmates' responses, by relating the question about accuracy with her previous experiences from the discovery-based activity to support her point. She describes instances that she observed of the pedometer not working, in order to motivate her conclusion on sensor accuracy. This suggests that the children were able to build an implicit knowledge of the limitations of the sensors through the discovery task—for example that their accuracy is dependent on the context in which they are used—which they were able to then bring to the table when discussing sensors in general.

However, during the discussion phase, the children's responses did not always convey a complete understanding of the topics. For example, in one session, a pair of children reflected that even when they did not have their fingers on the GSR sensor, it displayed a sensor reading. They discussed what this might mean: "*they're not quite accurate because when we took it out, there was nothing on the thing [sensor] – we didn't put our fingers in it, and it just changed the numbers*." This then triggered a discussion between the children and researcher, where the researcher explained that the sensor has no way of knowing whether or not someone has placed a finger on the sensor, and instead constantly measures resistance, which is not necessarily telling of its **accuracy** but rather of how **informative** it is in a particular context.

In sum, while the children were able to reason about the high level topics by drawing on their experiences with the Magic Cubes, the analysis suggests their understanding of the topics was not always complete. However, because these instances occurred in the reflective discussion, only two or three children in each session answered the questions that were asked about accuracy, reliability and sensor limitations; this is a limitation of the methodology, which means that it was not possible to fully analyse to what extent each child was able to abstract away from the task to reason about each topic.

8.7 Discussion

The findings from the study showed that the children were able to engage in critical thinking to a certain extent when reasoning about the data that they collected about their bodies and their environment using the Magic Cubes. In particular, from the transcribed conversations and their interactions, there was much evidence that they understood that some sensors are not always accurate and do not always reliably reflect phenomena that they are assumed to measure. They were also able to reflect explicitly on the IoT concepts they were introduced to – reliability, accuracy and how informative sensor data is. They did this when asked about the concepts directly during a reflective discussion. Not taking a sensor reading at face value and wondering how it can vary depending on what someone does with a sensor was an important lesson that enabled the children to think more deeply, for example, about what it means to measure GSR, and in what contexts it can be relied upon. To explore more how critical thinking manifested itself during the sessions I return to the research questions posed in this chapter, specifically:

> ***RQ 8.1:*** *Can discovery-based tasks enable children to think critically about sensors, sensing and sensor data in a classroom context?*
> ***RQ 8.2:*** *What are the components of critical thinking that occur during discovery-based learning?*
> ***RQ 8.3:*** *What mechanisms trigger critical thinking about IoT concepts?*

RQ8.1: Can discovery-based tasks enable children to think critically about sensors, sensing and sensor data in a classroom context?

As the findings demonstrated, the discovery-based activities did enable the children to critically reflect about how specific sensors work, beyond what their names suggest – for example, that GSR values are related to moisture on the fingertips, which can be influenced by stress. They were also able to reflect on how accurate or revealing the sensor data was from specific sensors, and how this changed when using the sensors in different contexts. These types of reflections were found to occur during the discovery task, where many instances were found of the children questioning whether the data that was displayed on the Magic Cubes in real time represented true values (e.g., how many steps they had taken), and reasoning about why it might not.

The findings suggest that one way this kind of reasoning was supported was through the activity that they were asked to do – which enabled the children to relate the data that the sensors displayed to their own experiences, in particular of their bodies. Promoting learning that was personally meaningful to the children and capitalized on their awareness of their bodies and environment (see [Jacob et al., 2008]) was central to helping them make the connections between the sensor, the data collected and how it mapped onto the underlying activity that was being measured (e.g. moving, breathing, answering an embarrassing question). In particular, by enabling the children to explore their personal data – such as GSR, step count and pulse – together with concrete and easy to understand visualizations of the sensor values, the activity facilitated them in directly relating the values that were displayed on the Magic Cubes to phenomena that they could feel or observe. These included how often their heart was beating, how stressed they felt, and how much they had moved. By being able to directly relate the data displayed on the Magic Cubes to experiences they could count (e.g., the number of steps they had taken) or feel (e.g., their own heart beat), in turn, enabled them to observe instances when the data that was displayed was inaccurate.

Interestingly, less reflection about data was observed when reading the values displayed on the Magic Cubes for the light and temperature sensors. This suggests that it was more difficult for the children to spot when a reading from one of these environmental sensors was wrong. This was due to the fact that it was not possible to establish a ground truth for these two sensors in the same way as for the personal sensors; they could not directly measure light and temperature themselves in the same way as, for example, counting how many steps they had taken and comparing it to the sensor reading on the Magic Cube. Instead, they had to take the reading at face value. While it is straightforward to relate an increasing value of light or temperature to a brighter or warmer place, it is harder to establish the accuracy of specific values in degrees Celsius or light level in lux without using another measuring device. This demonstrates that presenting data in a way that can be directly related to a personal, embodied experience that the child can relate to can provide a better grounding for them to reflect upon the accuracy or reliability of the data reading being shown.

Another way that critical thinking was supported during the discovery process was through unexpected sensor behaviors. The properties of the sensors that were used meant that they sometimes worked in ways that were ambiguous or counterintuitive. For example, the GSR value went down with stress level, instead of up; the pulse sensor reading was sensitive to changes in light; and the pedometer added steps on when the cube was dropped or shaken. Because these effects were readily observable, they promoted much verbal reflection between the children about how the sensors worked, and about when they broke their expectations. This suggests therefore, that a good strategy for promoting critical thinking is to provide activities which are meaningful to the child, but where the data collected with a sensor can at times be puzzling or be ambiguous (see [Rogers & Muller, 2006]). This makes them stop and think why it is showing a given reading, especially if it is contrary to what they expect.

RQ 8.2: What are the components of critical thinking that occur during discovery-based learning?

In this context, and for this age group, it was seen that the children were able to reason about the sensors while applying their understanding of how they work, experimenting with them and analyzing the data readings that they obtained using the Magic Cubes.

Through the discovery activities they were successful in achieving the first two envisioned outcomes that were set out for them, that is, (1) understanding what the sensor measures and how, and (2) reasoning about why and when the sensors may not be working as expected. The cognitive processes that led to these outcomes were seen to feed into each other in both directions. The children often *applied their understanding* of how the sensors work to *infer* why they were working in unexpected ways. For example, some children were able to apply their understanding of the fact that the pedometer measures how much the cube has moved, to reason why it did not add steps when walking without moving their hands, if the cube was placed on their wrist. Conversely, by *experimenting* with the sensors, and *analyzing* why they were not working as expected, they would refine their understanding of how the sensors worked. For example, observing that the GSR sensor reading did not change when the sensor was wet, led some to infer that it was measuring values related to moisture.

While the children were not explicitly asked to engage in a structured scientific enquiry process during the discovery activities, they engaged with the processes of experimenting with the sensors, analyzing the presented data and inferring its meaning, to a larger extent than expected. This suggests that there is much promise for designing open-ended, hands-on activities when the goal is to promote curiosity and critical thinking about data. This is in line with other research on technology-mediated exploration of data for children, where promoting student-initiated exploration of phenomena with a technology has been found to enable scientific enquiry, even if this is not explicitly asked of the students [Rogers et al., 2004; Rogers, Price, et al., 2002].

However, despite the positive findings that the children engaged in critical thinking about *specific sensors* during the discovery-based activities, there were limits to the level of critical thinking that they engaged in. Specifically, during the discovery-based activity, no instances were found of them discussing, evaluating and judging *sensors in general* – the third envisioned outcome that was set out for the sessions. To explicitly evaluate and judge the limitations of sensors in general, they had to be probed by their teachers or the researcher. In some ways, this is to be expected, given the study was run as a one-off session in each school, and that the concepts of accuracy and reliability in the context of sensors were only introduced to the children at the start of the session. However, it suggests that there are limits to what can be achieved with discovery learning alone, in particular in terms of how children can abstract away from a specific hands-on task to relate it to more general principles. This is supported by previous literature on discovery learning, which suggests that a level of cognitive guidance is important for enabling students to integrate the observations acquired from a hands-on, behavioral activity into more abstract patterns and principles [Mayer, 2004].

Nevertheless, the way in which the children based their descriptions of how accurate, reliable or informative sensors are in general during the discussion session was often by supporting their responses with what they had observed during the discovery process. While their understanding of the target concepts was not always complete, this suggests that the hands-on experience had a positive effect on enabling them to evaluate and judge the reliability of the sensors and their ability to accurately sense certain phenomena.

To facilitate a deeper level of critical thinking, where children can learn to abstract more from what they are asked to discover, they may simply need more practice and more in-depth discussion. If so, this suggests that the dovetailing of well-designed discovery activities and discussion during learning may be a good enough process by which to ask children of this age group to learn and reflect about other concepts in IoT.

RQ 8.3: What mechanisms trigger critical thinking about IoT concepts?

A variety of support structures were provided during each session to enable the children to verbally reflect on their experiences. These included working in pairs, field journals, and instructor support. It was found that the children used all of these support structures when engaged in the discovery activities. Turning to one of these forms of help, was most marked when they got stuck or observed an unexpected sensor effect (such as the GSR sensor not detecting a lie). Here, we observed them talking to each other about what to do next, checking the journals for guidance, or calling on the support of an instructor – all of which provided opportunities to verbalize and reflect on their experiences.

Finally, similar to Chapter 7, it was found that the discovery activities often led to highly visible, loudly spoken and performative interactions. As noted, the interactions were often playful and, in some cases, competitive. Examples included children exclaiming in surprise when unexpected sensor responses were observed, dancing around the classroom, and physically congregating around objects where exceptionally high or low sensor values were observed. This type of highly charged and visible interaction concurs with previous research that suggests such performative acts can facilitate collaboration and communication [Hornecker & Buur, 2006]. Here, they attracted the children to turn their attention to observe others around the classroom, and in this way promoted peer learning – as the children were able to monitor each other's actions and help other pairs when they noticed that their perceptions of the sensors are incorrect. They also helped the teachers monitor the activity in the class, and intervene at appropriate points when necessary.

In sum, this combination of the learning activity and the learning environment was effective at supporting the learning of critical thinking about sensor properties. This suggests it is helpful to have flexible scaffolding in place when designing for discovery activities that are aimed at teaching children to reason about computing concepts at a deeper level. Here, having the choice of asking others, observing others, having an instructor-led discussion or looking up suggestions, provided a number of mechanisms for this.

8.8 Summary

This study has shown how it is possible to encourage children to begin to understand that sensing isn't just about reading off data from a device; depending on how the sensor is used and in what context, sensor data can be inaccurate, unreliable or uninformative. This in turn means that sometimes the data from sensors can be relied upon, but other times that is not the case. Furthermore, understanding the basic principles of accuracy and reliability are important stepping stones for learning about other topics, for example, how to filter noise and capture patterns in datasets, and thinking critically about how the data that makes up a dataset can influence bias in IoT, AI and other paradigms. What this study has demonstrated is how to embed the process of critical thinking in learning about computing in such a way that enables young children to readily and enjoyably engage with these topics when just beginning to learn about computing. As such, it can better equip them with not just the ability to understand how an aspect of a technology works, but also the ability to question and probe more.

Both this study, and the study presented in Chapter 7 were carried out in one-off sessions at different schools. To explore further to what extent the Magic Cubes can support learning about these and other computing concepts over time, and to be made inclusive for a wider range of students than those in mainstream classrooms, the next study was run over a period of six weeks at a Special Education Needs college.

CHAPTER 9: THE MAGIC CUBES IN SPECIAL NEEDS SCHOOLS

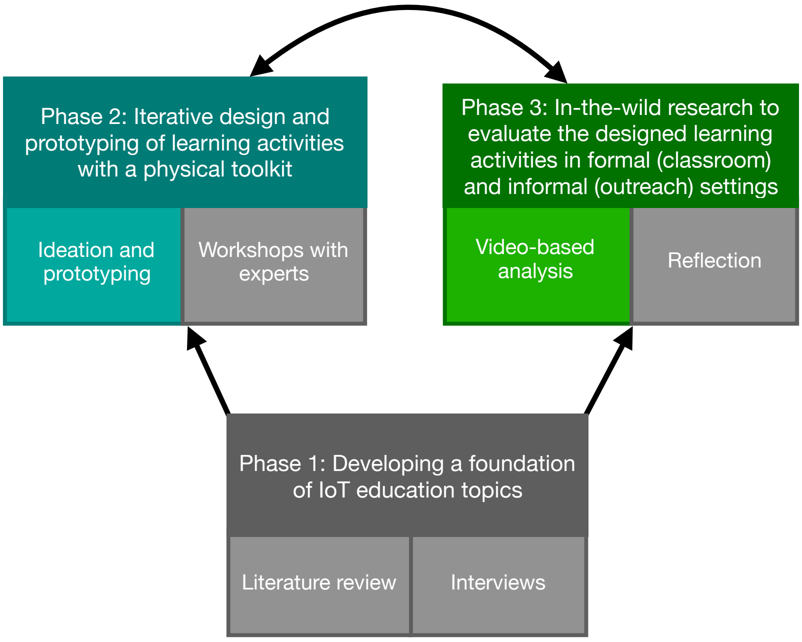


Figure 9.1: This chapter addresses the design of new activities aimed to teach children with a range of special education needs about computing using the Magic Cubes, and video analysis from an in the wild study where students completed these activities in their classroom.

While the studies presented in Chapters 7 and 8 investigated how the Magic Cubes can be used to introduce children to concepts related to sensing and IoT for one-off learning sessions, it was considered important to also investigate how they can lend themselves to learning over time. Therefore, the next aim of the research was to investigate how learning various aspects of conceptual understanding related to IoT using the Magic Cubes could be supported over time, by using them with a variety of task types to teach about computing topics of increasing complexity, over the course of a number of sessions.

Where one of the overarching aims of this research is to make learning about IoT accessible to wide audiences, it was also considered important for the research to go beyond mainstream classroom settings. The opportunity arose to collaborate with the Children and Technology (ChaT) lab at the University of Sussex, which specializes in research with neurodiverse children. Through this collaboration, a relationship was formed with a special education needs (SEN) college in England, which offered a computing class to its students. While the students in this college were much older than those in the previous two studies (16-19 years old, as compared to 8-12 years old), visiting the college with the Magic Cubes demonstrated that the students were very interested in learning with them, and their teacher thought that they would be a good fit for their entry level GCSE-track computing class. By drawing on previous research with tangible and physical interfaces, as well as on the literature about mixed special needs groups, a series of learning sessions were designed and conducted during a school term at the SEN college, using the Magic Cubes in a classroom with students aged 16-19. These sessions provided a range of learning tasks through a variety of discovery-based and coding activities, and emphasized the provision of appropriate conceptual scaffolding for learning about IoT.

By qualitatively analyzing the students' learning pathways with the Magic Cubes, as well as their subjective experiences during the sessions, I report on how the Magic Cubes, together with the designed learning activities, led to patterns of *collaboration*, *comprehension*, and *engagement* for a diversity of learners when learning about computing.

I discuss the lessons learned and, in particular, the benefits accrued from both the design of the *technology* and the *learning task* for interventions that are able to accommodate a mixed SEN environment.

9.1 Motivation and Research Questions

The argument for getting *all* school-aged children to learn about computing is now universally accepted. However, in debates about the best practices for teaching computing, little has been said about how to include learner groups that are often overlooked (for emerging work, see e.g., [Israel, Wherfel, Pearson, Shehab, & Tapia, 2015; Koushik & Kane, 2019; Somanath, Oehlberg, Hughes, Sharlin, & Sousa, 2017; Thieme, Morrison, Villar, Grayson, & Lindley, 2017]). In particular, there has been little research on the best ways for teaching computing for mixed special education needs (SEN) settings.

In special needs schools, classrooms are often mixed; students are rarely grouped in classrooms according to their primary diagnosis, such as Autism Spectrum Disorder (ASD), general learning difficulties or sensory impairments. Rather, classrooms include students with different profiles that have both distinct needs and distinct strengths, often with a larger spread in abilities than in mainstream classrooms. This poses a challenge for researchers and teachers: *how can the needs and strengths of students in a mixed SEN classroom be best supported to learn computing?*

Promisingly, the benefits of tangible and physical interfaces have been suggested to support the key learning challenges in SEN, specifically by providing multiple representations of abstract concepts, opportunities for physical manipulation, and through enabling collaboration [Falcão & Price, 2010]. However, while they have been explored in research for specific learning disabilities, and especially for students with ASD (e.g., [Farr, Yuill, & Raffle, 2010]), work on introducing them to mixed SEN classrooms is still limited. Moreover, the few studies that have been carried out on teaching *computing* through physical and tangible interfaces have been largely for one type of special need, or for one off sessions in the lab (e.g., [Virnes, Sutinen, & Kärnä-Lin, 2008]). Here, we are interested in how their novel, physical formats can be explored by students with mixed abilities in a more naturalistic setting – their classroom – with which they are familiar and used to learning in.

As chapters 7 and 8 have demonstrated, the Magic Cubes readily support the benefits of tangible and physical interfaces proposed by Falcão and Price [2010] for children in mainstream classrooms. Therefore, there appears to be much potential for students with special needs to also benefit from learning with them. This chapter is concerned investigating whether the properties of the Magic Cubes can also lend themselves to helping SEN students collaborate more and harness their ability to think abstractly when learning about computing. Moreover, this chapter is interested in the types of informal assessment methods that can be used to understand the students' learning and experience, beyond tests of conceptual knowledge, which can be inappropriate for a SEN context. Specifically, the study described in this chapter is concerned with addressing the following questions:

> ***RQ 9.1:*** *Can the Magic Cubes provide an experience that is collaborative, engaging and supports comprehension, for a spectrum of learners in a typical SEN school setting?*
> ***RQ 9.2:*** *What difficulties do learners with SEN face when interacting with the Magic Cubes? How are these overcome?*
> ***RQ 9.3:*** *What kinds of informal methods of evaluation are appropriate for assessing the students' experiences and learning?*

9.2 Methodology

The aim of this study was to assess the benefits of using the Magic Cubes in a different classroom context, namely, to support students with diverse special education needs when learning about computing. Specifically, the goal was to investigate what design aspects of the Magic Cubes and the learning task could support learning. The aspects of learning that were explored were *collaboration, engagement with the content* and *comprehension of computing concepts*, building upon the research investigating these in Chapters 7 and 8. Also these are three key aspects of learning that SEN students typically need additional support in [Falcão & Price, 2010; Holt & Yuill, 2014]. The class comprised students with mixed special needs and the activities were designed accordingly, bearing in mind the needs of individual students.

9.2.1 School Context and Participants

The school in which the study was run is a mixed gender, generic special school, which makes provision for a wide range of learning needs and disabilities; all pupils attending the school have an Education and Health Care Plan (EHCP) maintained by their local authority. The school has a total number of approximately 250 pupils between the ages of 2 and 19. The school is situated in a town in West Sussex, England, with 26.5% of pupils eligible for free school meals.

The participating students were all voluntarily taking the same computing course, that was part of an entry level GCSE-track computing curriculum. The study took place in their typical computing class group and classroom. A total of 11 students ages 16-19 (including 9 male and 2 female) participated in the study. This is a typical size of a classroom setting for UK SEN schools. The preponderance of male students in the class may have been due to the fact that the school had a high ratio of male to female students, as well as them electively enrolling in the computing class and having a prior interest in computing. The students had a range of special education needs (see Table 9.1). The most prevalent primary diagnosis was ASD (n=5), followed by moderate and specific learning difficulties (n=3), which is representative of UK SEN demographics [Department for Education, 2019]. The class had one main teacher, as well as two key workers (also a typical set-up), who supported the students with communication (e.g., through sign language) and learning tasks. Both the teacher and the key workers were present and actively involved in all sessions. The students were all familiar with each other from working together as a class and from other group work; they were asked to choose their own groups for the sessions.

Name *	Gender	Group	Primary Diagnosis
Jason	M	G1	Autism Spectrum Disorder
Keith	M	G1	Acquired Brain Injury
David	M	G2	Autism Spectrum Disorder
Eric	M	G2	Specific Learning Difficulties/ Speech and Language
Ali	F	G2 / G3	Hearing Impairment/ Moderate Learning Difficulties
Curtis	M	G3	Autism Spectrum Disorder
Fabian	M	G3	Social, Emotional, Mental Health
Neil	M	G4	Autism Spectrum Disorder
Teddy	M	G4	Autism Spectrum Disorder
Lily	F	G5	Moderate Learning Difficulties
Gary	M	G5	Other, not specified

Table 9.1: Description of the students' profiles. *All names have been changed to protect the participants' anonymity.

The computing class in which the study was run did not deal specifically with teaching IoT topics, however, the students had some experience experimenting with physical computing platforms like the Raspberry PI, and had in this way been introduced to the topics of sensors and actuators as part of their computing class. In this study, we worked closely with the classroom teacher to ensure that the sessions we planned for aligned closely with the curricular goals of the class, as is elaborated in more detail below.

9.2.2 Session design

Six weekly 90-minute sessions were planned during the students' regular computing class timeslot. Prior to the sessions, we[4] communicated with the class teacher about the demographics of the class and the specific needs and interests of the students, and integrated his responses into the planned learning tasks. The intervention as a whole was intended to cover a number of computing concepts chosen to be in line with both the UK national computing curriculum [UK Department of Education, 2016] and the aims of the computing class that the students were enrolled in. For this study, a wider range of learning activities was planned over a period of six weeks than those in the studies presented in Chapter 7 and 8. Because of the audience – where the students had a diverse range of abilities, and where a number of the students struggled with abstract thinking – it was decided not to focus explicitly on critical thinking skills. Instead, the sessions were designed to fit into the curriculum of the classroom, and focused on teaching the students about basic hardware and programming concepts. Based on the curriculum and discussions with the classroom teacher, it was decided that the six sessions would address the following computing topics:

1. Understanding the functionality of core hardware components in a computer
2. Understanding the functionality of sensors and actuators
3. Understanding the functionality of wireless Bluetooth connectivity
4. Understanding and writing basic algorithms

[4] To run the studies and help with the activities, 1 to 4 other researchers, apart from myself, were present in each session, each walking around the classroom and helping the groups when needed. Two of the researchers, Lena Nagl (LN) and Grazia Ragone (GR), who were Masters students at the University of Sussex, contributed to the study from the session design to the data analysis. The other two researchers, who were sometimes present during sessions, supported the practical aspects of running the sessions, but were not involved in the data analysis.

5. Understanding and programming *if/else statements*
6. Understanding and programming *for loops*
7. Understanding and programming *bitmaps*

Similarly as in Chapters 7 and 8, the topics chosen reflect an emphasis on teaching about IoT-relevant physical hardware and sensor data – based on the suggested IoT topics that emerged from the interview study in Chapter 5.

To design the six sessions, empirically-grounded design considerations were taken into account from an exploratory study of a SEN classroom [Falcão & Price, 2010] and a systematic literature review about technology design for SEN learning [Börjesson, Barendregt, Eriksson, & Torgersson, 2015]. These were: (i) capitalizing on embodied interaction to promote concrete, kinesthetic learning and collaboration between peers; (ii) enabling success for students of diverse abilities through short, attainable and conceptually scaffolded tasks; (iii) providing the students with instructions through multiple representations (verbal, visual and written); (iv) providing opportunities for reflection on and consolidation of newly learned concepts; and (v) enabling flexible support from the instructors.

It was decided that three of the six sessions would utilize the Magic Cubes toolkit to introduce new topics. The first of these Magic Cubes sessions replicated the *making* learning activities used in the study carried out by Johnson et al. [2016], and the *discovery-based* learning activities used in Chapter 7. In the latter two Magic Cubes sessions, the students carried out programming activities – which had not been previously formally evaluated. Each of these Magic Cubes sessions was followed in the subsequent week with a toolkit-free task, designed to consolidate the concepts that were learned while using the toolkit. This was done to provide the students with opportunities to reflect on the computing concepts they had learned, as well as to enable us to gauge the students' understanding. In addition, these allowed us to proactively shape the learning activities based on the observed needs and comprehension of the students.

It was considered important during the sessions to scaffold the tasks in such a way that students had to complete simple tasks before moving onto more complex ones. This was aimed to enable them to build up their knowledge over time. Each pair of students was given as much time as needed for carrying out each of the tasks during the sessions. Hence, completion of tasks and the timing for moving onto next ones was relatively unstructured. Table 9.2 describes in detail the activities and motivation for their choice for each session.

9.2.3 Procedure

Before we arrived at the first session, the teacher explained to the students what was going to happen and what they would be learning in the following six weeks. The parents of the students were informed of the project and gave their consent for their children to participate and for data to be recorded. At the beginning of the first session, the researchers were introduced by the teacher. The students were informed about the purpose of the research, and it was explained that the videos and images of the students would not be shared with anyone other than the researchers. The students were given opportunities to ask questions, and then asked if they would like to take part in the research and whether they would mind being filmed, and all consented.

Table 9.2: Rationale for each of the six sessions and details of the learning activities in each session.

Week 1. The first session consisted of making and discovery-based learning activities. The aim of the activities planned for this session was to enable students to understand the *functionality* of physical computing hardware components–sensors, actuators, Bluetooth connectivity, and how these components work together. The students were first asked to assemble a MakeMe cube, which is a smaller version of the Magic Cube, as described in Chapter 6. Next, they completed two discovery-based tasks with the MakeMe cube – which were replicated from a study by Johnson et al. [2016]. These were (i) shaking the cube to map color of light to speed of acceleration and (ii) drawing 3D shapes in the air to elicit specific colors of light inside the cube. After completing these tasks, the students were given the Magic Cubes, and asked to complete the three discovery-based tasks that were described in Chapter 6: covering the light sensor to turn on the embedded neopixel light, blowing hot air into the cube to elicit a change in the animation, and again shaking the cube to change to color of light. Finally, the students were given three other discovery-based tasks. These used the same sensor-actuator mappings as the previous tasks, but added the element of Bluetooth connectivity, to enable the students to explore how the cubes could communicate wirelessly. Specifically, blowing hot air into one cube elicited an animation effect on the other cube; covering the light sensor on one cube caused the neopixel light to turn on in the other cube; and shaking two cubes together caused the colors of the neopixel lights in both cubes to mix together – specifically, shaking a cube with a blue light and a cube with a red light changed the lights in both cubes to purple.   **Week 2**. The students created slide presentations about their first experience with the Magic Cubes. In the presentations, they were asked to include what they had learned during the first session, what they thought of the Magic Cubes, and what they thought about the research study. This was done as a way of encouraging the students to reflect on the concepts they had learned, and to provide more insight into their experiences.   **Week 3**. In this session, the students were introduced to programming the Magic Cubes using the block-based ArduBlock programming environment. This was designed to enable the students to move from understanding the *functionality* of the embedded hardware in the cube, and to being able to *control* the hardware components through programming basic algorithms together with if/else statements. The first task they were given was to program the Magic Cube as a night light – by checking if the light level sensed by the cube was below a certain threshold, and if so, instructing the program to turn the embedded neopixel light on. They were provided with step-by-step instruction sheets with both written guidance and visual representations of what the completed code should look like. The task was segmented into a number of steps.   **Week 4**. The students were asked to design and create a paper prototype of their own "Internet of Things" device, by using their knowledge of sensors, actuators and wireless connectivity. They were then asked to explain this paper prototype, what sensors and actuators it would use, whether it would be connected to another device and how it would work. This was aimed at enabling the students to creatively apply their understanding of how the physical hardware that they learned about in the previous weeks works, and in what contexts it can be used.   **Week 5**. The students were asked to continue programming the cubes. Specifically, they were asked to program their own animations on the LED matrix of the cube using ArduBlock. This more open-ended activity was designed to enable the students to further their knowledge of writing algorithms and to additionally learn about writing *for loops* and creating *bitmaps*. They were given a step-by-step instruction sheet instructing them how to create an animation, along with space where they could draw out their animation designs to help them turn the designs into 8x8 bitmaps that would fit onto the LED matrix of the Magic Cubes.   **Week 6**. In the final week, the students were asked to conduct video interviews with their partners to ask each other about their overall experiences (this method was inspired by [Portelance and Bers, 2015]). This assessment method was selected to enable the students to voice their perceptions about their experiences during the 6 weeks with their peers, and discuss what was fun, interesting, difficult or boring for them.

Throughout all the sessions, the students were asked to work in pairs or groups of three. This was done to encourage collaboration and dialogue while learning. The students also chose their own partners so as to feel comfortable with the person they had chosen. Throughout the six weeks, the majority of the students remained in the same pairs (see Table 9.1). There were two exceptions. In week 1, Fabian, a new student from Italy who had limited English fluency, worked with an Italian researcher (GR), who helped him by translating the verbal instructions. Later in the same session, he worked with Curtis and Ali (G3). From week 2 onward, Fabian worked only with Curtis. Ali, who was in a pair with Curtis (G3) in week 1, was absent for three sessions due to a conflicting personal appointment. In weeks 5 and 6, she rejoined the class, and joined a group with David and Eric (G2). Additionally, in week 4 – the week in which the students completed a design challenge – six of the students were absent due to a conflicting field trip. Therefore, in this week the five students who were present worked either in different pairs or individually.

9.3 Data Collection and Analysis

During each session, continuous audiovisual data was collected of the students' dialogue, interactions with each other and interactions with the Magic Cubes and materials provided. Placement of multiple cameras throughout the room ensured that both the students' interactions in groups and the overarching classroom interactions (i.e., between groups, and between the students and instructors) were continuously audible and visible. In addition, all of the researchers wrote field notes.

No formal methods of assessing the students' knowledge (e.g., through pre- and post-tests) were used. This is because the sessions needed to be designed to not be stressful for the students. It was also assumed that trying to assess the putative gained declarative knowledge through traditional assessments would have likely triggered stress. Instead, the more open-ended and creative evaluation techniques used for the sessions in Weeks 2 and 4 – i.e., slide presentations and a design challenge where the students were asked to design their own IoT artefact – were used that enabled them to reflect on what they had learned in what was intended to be non-stressful. In the final session in Week 6, the students also conducted peer video interviews with each other about their subjective experiences, based on a similar method proposed by [Portelance & Bers, 2015]. This method was employed to enable the students to reflect in a manner it was assumed they would be comfortable with. The researchers also interviewed the class teacher about each of the sessions. Together these methods provided different perspectives on the students' engagement, learning outcomes, and overall experiences.

9.3.1 Foci of audiovisual analysis

The focus of the analysis of the audiovisual data was on how the Magic Cubes and the associated task types (i.e., making, discovery, coding) supported collaboration, comprehension and engagement in the different sessions. Here, the analysis of *collaboration* followed Roschelle and Teasley's perspective that collaborative learning entails the 'continued attempt to construct and maintain a shared conception of a problem' [1995]. Through this lens, the analysis focused on whether and how each student was able to support the learning of others, by physically sharing the technology, instructing their partner and reinforcing others' learning through dialogue. To analyze *comprehension*, we examined how engaging with the technology and learning tasks led to the students' reflection on the target learning concepts. Hence, comprehension was analyzed more as a process, rather than an outcome. The analysis focused on dialogue between the students and instructors, indicating comprehension, or conversely, dialogue that indicated lack of understanding. The analysis of *engagement*, was informed by Price and Falcão's framework [2011], which characterizes how different foci of attention all interplay during the learning process—for example, focus of attention on the technology, on tangential activities, and on the explicit learning outcomes. In analyzing engagement, therefore, the focus was on the strategies the students used to regulate their attention to the technology and the learning tasks, and what aspects of the learning task made this easier or more difficult to do.

9.3.2 Analytic procedure

The analysis of the audiovisual data was done by inductively coding and categorizing meaningful events related to collaboration, comprehension and engagement, as framed above. In contrast to the studies presented in Chapters 7 and 8, with the support of LN and GR, it was possible to hold detailed, collaborative data sessions [Jordan & Henderson, 1995]. In these data sessions, myself (ZL), LN and GR discussed our field observations and watched segments of video together, focusing on the three foci of analysis. Specifically, we discussed events where the students' *comprehension*, *collaboration* and *engagement* were seen to be supported by the Magic Cubes and learning activities, and where issues were seen to arise. To aid the analysis, annotations were added to the video recordings after the collaborative discussions to index where the observed phenomena occurred in the social and temporal context of the tasks. I then iteratively categorized the observed events related to collaboration, comprehension and engagement into themes, based on recurring instances. These were then refined with the students' and teachers' perceptions of their learning, as identified through the interviews.

9.4 Findings

Overall, the sessions were found to be a predominantly positive experience for the students, as indicated by both the students' responses during the peer interviews and by the teacher's feedback. In general, most of the students stayed engaged throughout the six sessions. Much collaboration was observed both within groups and between groups, although the patterns of collaboration were qualitatively different between the different learning activities. We also found that comprehension of the computing concepts was supported by the social and embodied nature of the learning that took place. While the students faced a number of issues related to their cognitive and physical difficulties during the six weeks, these were often addressed by the varied support structures embedded in the classroom. Next, the findings are presented in terms of: 1) *informal method used to evaluate the students' learning and experience* and 2) *the audiovisual analysis of interaction.*

9.4.1 Informal methods used to evaluate the students' learning and experience

Throughout the sessions, a number of informal methods were used to help us understand the students' experiences with using the Magic Cubes and the extent to which they promoted successful learning. The findings arising from these methods are described below, in terms of the *teacher interview, peer interviews* and *artifact-based methods.* Next, I summarize the feedback that the classroom teacher provided about the sessions.

Teacher interview

The classroom teacher provided feedback in an interview conducted after the last of the six sessions. This was transcribed and is described below in terms of *overall feedback, the value of different types of learning activities, the importance of flexibility and self-contained sessions* and *the practical value of the sessions*.

Overall feedback. The teacher indicated that the sessions were overall a success, stating that, *"it's been very positive, I don't think there's any negatives."* Specifically, he felt that sessions "*really worked across what was actually a wide range of abilities, and different sorts of interests within the class."* He stated that he was *"really impressed by the way the students have been so engaged throughout. It's been sustained engagement I think and between all of the different activities*." He remarked in particular that the level to which Teddy (ASD) was able to stay on task throughout the six weeks surprised him: *"he's very bright, but he's usually very much on his own agenda. But he really did stay very focused on it."* When prompted further about whether he observed anything else that surprised him in the way other individual students participated in the sessions, he said *"it would be hard to pick anyone out, because they just really all found something in it."*

The value of different types of learning activities. The teacher found much value in the fact that the sessions included not just programming, but also making and discovery learning with the physical cubes. In particular, he felt that the process of programming code on the computer and uploading it to an external device gave *"a sort of added dimension"* to the students' understanding of what programming is and how it can be applied. Specifically, he said: "*It showed them the idea that you write a program, and then it can actually be loaded onto a device, rather than it just taking place on the PC."* He felt that the programming tasks that were designed to be done with the Magic Cubes also fitted well with what the students had done previously in class: "*they've done a little bit of coding before, they've done some Scratch programming, but very small amounts. I thought that was particularly good because of the way that was transferable onto the cubes.*"

In terms of the making and discovery-based tasks, the teacher highlighted how the physicality of the cube provided an added dimension to learning about hardware: *"I thought the making was great just because literally it's physical. You know, putting something together makes you feel much more connected with it."* He also discussed how experimenting with the sensors through the discovery-based activities enabled the students to think creatively about the potential uses of sensors: *"I think that was really nice that they just kind of came up with different possibilities of sensors, and what they can be used for."*

The importance of flexibility and self-contained sessions. During the sessions, there were a few instances of students being absent due to other appointments or school activities. The teacher mentioned that this happens quite often at the school, and discussed how the flexible and self-contained sessions were important in making the students be able to join in, according to their schedule, without feeling like they were behind if they missed a session. In particular he said that each of the sessions we ran *"worked like a separate sort of thing where it didn't matter that someone hadn't come in – so I think that was a good structure."* Therefore, the fact that the sessions built on each other to an extent, but were not a continuation of each other, was found to be important for this school setting, where absences are to be frequently expected.

The practical value of the sessions. The teacher also emphasized the value of the sessions beyond the academic, especially in terms of enabling the students to work with a group of people who are external to the school: *"it's been a really valuable experience for them in terms of having visitors, the fact that they're working with people that they don't know – for some of them that's quite a big deal. So there's huge value in this beyond the obvious. […] I think they were really proud to be part of it."*

Peer interviews

The peer video interview method, which was used during the last session, was found to be successful as a way of enabling most of the students to discuss their experiences during the Magic Cubes sessions. In particular, it provided insights about what they enjoyed the most during the sessions, and what they found difficult. Responses related to the latter were often a revealing supplement to the video data. For example, they helped us understand why some students became disengaged during specific parts of the sessions. However, it was found that the peer interviews were not as informative about what the students had learned – as their responses were not sufficiently detailed to evaluate the gaps in their understanding. Next, I discuss the findings from the interviews in terms of *insights about the peer interview process, what was enjoyable, difficulties encountered,* and *what was learned.*

Insights about the peer interview process. Before starting to interview each other, the students were given a list of example questions to ask each other, which included: "what was your favorite/least favorite lesson," and "what would you change about the sessions?" They were also encouraged to come up with their own questions to ask each other. However, none did so – instead, they asked each other the example questions provided.

Most students readily participated in the peer interviews. However, two students struggled to participate. Specifically, Ali (Hearing Impairment, Moderate Learning Difficulties) sat together with her partners, Eric and David during the peer interview, however, she was shy to speak to the camera, and preferred not to answer the questions in front of the camera, letting her partners answer instead. This is despite the fact that her key worker sat next to her, and interpreted questions that she might not have heard in sign language. Neil, who had the most severe form of ASD of the students in the class, and was less verbal than the others, had trouble responding on topic to questions that his partner, Teddy asked him, as illustrated by the snippet below.

> *T: Which one was your favorite lesson and why?*
> *N: I like ICT because I like doing computing.*
> *T: Oh, fair enough! What was your favorite thing to make?*
> *N: [pause, no response]*
> *T: It has to be around these codeme cubes… [pause] oh anyway, let's leave that. What did you learn?*
> *N: Did I learn about what?*
> *T: Learn about code cubes.*
> *N: Right*
> *T: Ok..*

This suggests that for these two students, the peer interview method was not the right format to be able to trigger reflection on their learning experiences.

What was enjoyable. Beside the two students who had trouble responding to the questions, the students' responses indicated that, overall, they enjoyed the experience of learning about the Magic Cubes over the period of six weeks. For example, David said that he *"thoroughly enjoyed all of it"* while Fabian said that his least favorite lesson was the last lesson – *"because it was the last lesson."* Teddy said that *"the reason why I liked it is because it's just more than sitting down in a normal ICT lesson where you slave away on a computer* *while typing a document."* Moreover, the students' favorite lessons spanned the full range of activities planned with the cube. A roughly equal number of students said that their favorite sessions were those that included making and exploring the cube through the discovery-based activities (Jason, Teddy, Keith, Lily, Curtis), as those that said their favorite sessions were those related to programming (Fabian, Gary, Curtis, Eric).

Difficulties encountered. The interviews also revealed what the students' least favorite activities were and why. Their answers provided insights as to what was difficult for the students, in ways that were not always evident from the audiovisual data. For some of the students, the least favorite activity was the last programming activity, in which they had to make an animation. The students noted that the last session with the Magic Cubes, in Week 5, where they had to build an animation, was too difficult. In particular, Jason commented that the coding in this session was *"very hard and impossible to do."* This suggested that the activity may have been too big of a jump from the previous session or not sufficiently scaffolded with appropriate instructions. Although Curtis said that he enjoyed the animation programming session, he suggested that it would have been improved by a longer introduction at the beginning to make clear what was expected: *"I would change the way [the session] is first presented at the start."*

Another finding from the peer interviews was the frustrations that the students experienced when the software failed, or when the Magic Cubes proved to be inaccessible for them. For example, for Keith (Acquired Brain Injury), the making activity where the students were asked to assemble the cube was the one that he enjoyed least, because he found the assembly of the cube *"fiddly."* To clarify what he meant by this, a key worker asked if he would have preferred that the making would be easier to do with one hand, to which Keith said yes. The fact that he struggled to use one of his hands was something that we did not know, and which was not readily evident from the video data. Moreover, G2 (David and Eric) discussed their frustration when the Arduino software had to be restarted, and they lost their work: *"I didn't particularly enjoy last week when I had my work deleted by accident."* David then went on to discuss how the programming software could be changed to avoid this problem in the future: *"I would program it so that it backed up automatically, so to save what happened to Eric and I so it wouldn't happen."*

What was learned. While the peer interviews were informative in terms of understanding what the students enjoyed and what was difficult for them, the method was less informative in terms of getting a sense of the concepts they learned, and the concepts with which they struggled. While they all asked each other questions relating to what they had learned, their responses were often broad. For example, Eric said, *"I learned a lot of coding and stuff."* The most detailed response to this question was from Teddy, who said, *"Oh we learned how to construct [MakeMe] cubes, we learned how to do a bit of animation using the code such as 1 means on, 0 means off, heat sensors, light sensors, motion sensors, shaking it about, you know what I mean."* However, the questions they asked of each other were not enough to reveal just how much they understood about the hardware and programming constructs.

Artifact-based methods

The artifact-based methods, that is, the slide presentations (week 2) and the design challenge (week 4), were found to be successful at getting the students to reflect on what they had learned in previous weeks. For the slide presentations, the students received few instructions other than to present their experiences from week 1, and to discuss what they had learned. Due to the school's computer infrastructure, we were not able to keep the slides that they created, which limited the extent to which the presentations could be analyzed. However, when watching their presentations, we noted how many of the students were able to discuss in detail how the Magic Cubes worked, in terms of what the different components that were embedded in them did. For example, they presented at length how different types of sensors had worked, and how connecting two cubes together through Bluetooth enables new types of functionality that are not possible with just one cube. In this way, they were able to explicitly reflect on the previous week's activities.

For the design challenge, the students were asked to design their own smart device that included sensors, actuators, and wireless connectivity. The students demonstrated much creativity during this activity, and we found that they were able to transfer the concepts of sensing and actuation to objects that were relevant to their lives. For example, Teddy decided to redesign the fire alarm. He thought that the current fire alarm in his home turned on too often when there was no fire, and found the level of noise that it generated "*unbearable*." He therefore designed a fire alarm that measured heat rather than smoke, and actuated the alarm in what he thought to be a less obtrusive and annoying way – through a bright light. Another example of a creative design was that of Jason and Lily, who worked together to create IoT devices for their pets. They envisioned wearable devices for their pets that would be connected to a mobile phone. The devices would let them play with their pets as well as monitor when they may have gotten hurt – for example, by being able to sense when the pet had not moved for a long time. In sum, based on an analysis of the students' designs and their rationales for them, it was evident that they had learned about the differences between distinct types of hardware components, and that they were starting to think about how simple algorithms could control hardware – in the case of Jason and Lily, for example, how the amount of time a pet had not moved for might mean it is time to check in wirelessly.

In sum, the teacher and peer interviews and the artifact-based methods presented in this section, were all revealing in different ways. Specifically, the teacher and peer interviews were effective in revealing the perceptions of the students and teachers in terms of what was successful about the designed learning activities with the Magic Cubes, and conversely, what led to disengagement or frustration. The artifact-based methods, in turn, were seen to be effective in getting the students to reflect on what they had learned and apply this to different contexts – such as designing their own IoT devices that appropriated sensors, actuators and wireless connectivity in ways relevant to their own lives.

Next, I describe the key findings from the audiovisual analysis of the students' interactions—both with the Magic Cubes and with each other—during the Magic Cubes sessions. This type of analysis complements the analysis of the use of the in situ reflective methods described above by providing a systematic overview of emergent themes across all the sessions based on observations of what happened.

9.4.2 Audiovisual analysis of interaction with the Magic Cubes

The findings from the analysis of audiovisual data are structured in terms of the kinds of *(i) collaboration*, *(ii) comprehension*, and *(iii) engagement* that were observed to take place during the sessions.

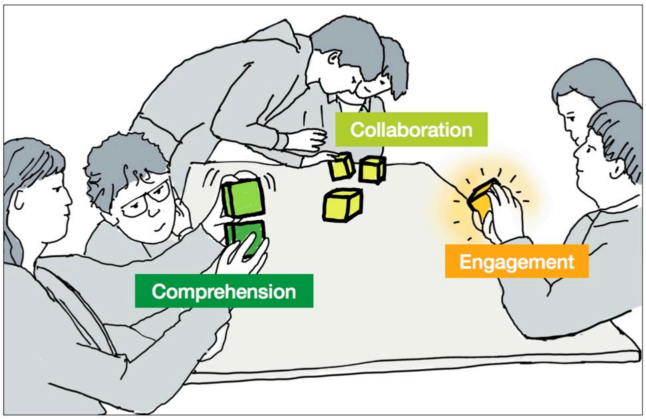


Figure 9.2: A sketch showing the set up of the discovery-based tasks, where students worked with the cubes in pairs around a table. The three constructs related to learning that were analyzed were the students' collaboration, comprehension and engagement.

(i) Collaboration

By collaborative activity in this setting is meant: individuals in pairs sharing control of task-related materials, visually attending to each other's actions, and verbally discussing the task. In the analysis, the following are examined: a) collaborative trends for each task, across pairs, and b) pairs' collaboration patterns throughout the intervention.

Overall, the majority of students were seen to actively collaborate on all of the making, discovery-based and programming tasks. However, the nature of the collaboration that took place was qualitatively different between learning tasks. Next, the patterns of collaboration that were observed throughout the sessions are presented. These are labeled as: *'Fluid' collaboration in unstructured, discovery-based tasks*; *'Static' collaboration and division of labor in programming tasks*; *Unprompted support of each other within groups*; *Sharing* *successes;* and *Breakdowns in collaboration*. A distinction is made between 'static' and 'fluid' collaboration patterns, where the former refers to collaboration where the students were observed to self-assign themselves to specific roles during a learning activity (e.g., reading out the instructions or programming), whereas the latter refers to collaboration where this type of role division was not observed.

'Fluid' collaboration in unstructured, discovery-based tasks

The making and discovery-based tasks in week 1 were carried out using only the Magic Cubes without being connected to a computer. In this session, the students were sitting around two tables, and engaging with tasks that involved unstructured exploration of the Magic Cubes. Collaboration within pairs appeared to be fluid, in the sense that the students in each group frequently watched and mimicked the others. The students were seen to take turns exploring the cubes' functionalities and discussing the hidden effects together. In particular, when new discoveries were made of the hidden sensor effects instantiated in the cubes, the students explicitly shared their cubes with their partners, by showing each other how the sensor effects worked, handing the cubes over, and instructing each other. This trend occurred across all pairs.

It was observed that in week 1, collaboration also occurred frequently *between* groups. For example, in the task in which the students first put together the Magic Cubes, they were not told how the cubes would function once they were assembled. After two students, Teddy and Neil (G4), finished assembling the cube, Teddy was quietly told by one of the instructors to *"try shaking it"*. As he did this, the light inside the cube turned on for the first time. Two nearby students, who were looking at Teddy, exclaimed *"wow!"*, which in turn led to everyone at the table looking towards Teddy's cube. Immediately after, all three pairs sitting at the table started shaking their cubes.

It was observed that the pairs worked at their own pace, as evidenced by them working on different tasks at any given moment in time. Between pairs, the students were seen to visually attend to each other's discoveries, in particular when someone in another group verbally called attention to their discovery. For example, Teddy, who was one task ahead of Lily and Gary (G5), discovered a sensor effect that entailed blowing hot air into the cube's temperature sensor in order to produce a growing fire animation on the LED matrix. When he successfully elicited the fire animation, he exclaimed *"hey look, I made fire!"*, pointing the LED matrix toward Lily, who responded *"oh, cool!"*. It was observed that once Lily and Gary moved to this discovery task, they immediately copied the action they had previously observed Teddy doing, without testing any other actions on the cube, suggesting that they had implicitly learned the sensor effect by observing Teddy's actions.

'Static' collaboration and division of labor in programming tasks

Collaboration patterns both within and between groups were found to be qualitatively different during the programming tasks, when the students were sitting in rows and facing computer screens, rather than at the large tables without computers. Within groups, the students implicitly divided their roles when collaborating. Specifically, in most pairs, one student held the instruction sheet and read aloud the step-by-step instructions, while the other controlled the programming software. This may have been because it was more convenient for one student to consistently access the keyboard and mouse than to share control. In all except one group (G4), the students were seen to point to the screen throughout the learning task, and to discuss where to place the programming blocks in the programming environment.

During the programming tasks, collaboration between groups was also observed to be far less frequent. The students occasionally observed the actions of those around them, but their attention was predominantly towards the computer screen used within their group. When observation of other groups occurred, this was most often tied to "loud" events in which the other group verbally expressed excitement after they had uploaded their code to the Magic Cube, or physical events in which the other group was shaking, or otherwise manipulating their Magic Cube in a way visible to others. An example of this was a pair successfully uploading their "night light" code in week 3, and calling the teacher over to show off what they had achieved, then subsequently reaching the cube toward the ceiling light. At these points in time, the students in their proximity looked over toward their peers, and provided them with positive reinforcement (e.g., *"oh, wow!"*).

During observed instances of talk between groups, while working on the programming tasks, it was found that there were no cases of spontaneous sharing of code, or of discussing the programming concepts. Instead, the students mainly relied on the instructors, rather than their peers, for support with the programming. In one instance, in attempt to promote more collaboration *between groups* during programming, the instructors prompted a pair to help another. Specifically, Curtis and Fabian (G3), who were ahead of the others, were encouraged by one of the instructors to walk over to Lily and Gary (G5) and explain to them how to make two images display on the LED matrix in sequence, in order to create an animation. Curtis verbally instructed Lily and Gary on how to put blocks together in the programming environment in order to create an animation. In doing so, he led them through the trial and error process that he and Fabian had previously followed when trying to understand the concepts of sequences and delays. Specifically, he told Lily and Gary to program two images in sequence and upload the code. When they did so, the LED matrix on the cube began to flash rapidly. Curtis then explained why this was happening saying, *"that's why it looks so red… cause it's going so fast"*. He explained that they needed to add "delay statements" after each image in order to instruct the cube for how long to display each image. Lily asked him to clarify where the delay statements should go. Once Curtis confirmed that they had formatted the code correctly, Lily and Gary then started to independently experiment with the delay variable values, while Curtis and Fabian watched.

Unprompted support of each other within groups

Throughout the intervention, the students were often seen to actively help each other out within groups when their partners experienced difficulties. For example, in the programming tasks, David (ASD, G2) took the role of reading out instructions to his partner, Eric (Specific Speech and Language Difficulties), who had substantial challenges with reading. Similarly, Curtis (ASD, G5) read out the instructions to his partner Fabian, who was not fluent in English, while Fabian controlled the mouse and keyboard. Jason (G1) also assisted his partner, Keith – who had limited use of one of his hands – in assembling the MakeMe cube in the making tasks in Week 1. In the discovery-based tasks, the students were seen to work together to come to the same level of understanding. For example, Jason was often faster than his partner, Keith, in discovering the sensor-actuator mappings embedded in the cubes. However, Jason was proactive in helping Keith to understand the concepts before the pair moved onto the next task. In one instance, when Jason had discovered an effect related to Bluetooth connectivity, which Keith had not, he showed Keith how to elicit the effect, while verbally explaining how it worked. The two then elicited the effect together by sharing control of the cube, resulting in them sharing a high five.

Sharing successes

A finding throughout the sessions was that the students consistently shared their successes with others after completing the tasks. Those who had successfully completed discovery-based tasks, or uploaded a new program to the cube, often drew attention from nearby peers, especially through verbal exclamations (e.g., *"I got it!"*). Moreover, they often stopped instructors who were walking past, in order to show off their discoveries, for example, by waving a cube in the air. Such instances were often met with positive feedback from their peers (e.g., *"cool!"*), and praise from the instructors (e.g., "*well done!*"). These moments were facilitated by the form factor of the cube making it easy to show off to others, for example, by waving the cube in the air and by tilting it towards someone on the other side of the table.

Breakdowns in collaboration

The exception to the collaboration patterns observed within groups was Neil (ASD, G4) and Teddy (ASD, G4). According to the class teacher, Teddy is normally able to grasp concepts quickly, but struggles with maintaining attention, and especially joint attention and often *"does his own thing"* during class lessons. Neil does not often verbally communicate, and it is often unclear whether or not he is actively attending to the class activities. In week 1, for the first thirty minutes of the exploratory making- and discovery-based tasks, Neil and Teddy were seen to both collaboratively engage with the learning tasks while sharing a cube. In particular, the pair was observed to mimic each other's actions when trying to elicit colors and animations on the cubes. This indicates how both Teddy and Neil were able to pay attention to each other and their respective progress with the task. However, towards the end of the session, Neil became disengaged and withdrew from actively taking part in further tasks. It was observed, nevertheless, that he was still visually focused on what others were doing, and filled out the worksheet appropriately when Teddy discovered the sensor effects. However, he did not pick up the cube himself, or test out the effects that Teddy had discovered, unless prompted by one of the instructors. Teddy continued to engage in collaborating not with Neil but with others nearby, when Neil became disengaged from the activity, for example by discussing and sharing his insights on the sensor effects with others. The class teacher noted that this behavior surprised him, in a positive way, given his previous experience with Teddy.

In the programming-based tasks, Teddy was seen to take control of both the instructions and the computer keyboard and mouse, while Neil was disengaged from the programming tasks. No discussion took place within the pair, although Teddy often called over to one of the instructors to ask questions. When asked by an instructor if he wanted to have a go at helping with the programming, Neil replied that he did not. It could be that the physical nature of the tasks in week 1, where no desktop computers were used and no static division of labor with a partner was required, made it easier for Neil to participate in collaborative activity. However, because he gave very short and off-topic responses in the peer interview when asked about his experiences with programming, it is unclear why he then became disengaged in the latter sessions.

(ii) Comprehension

In this section, I report on how comprehension of the computing concepts unfolded as the students interacted with the interface, instructions, and programming environment during the learning tasks. The observed comprehension patterns are broken down under the following headings: *The role of instructions and instructors in open-ended exploration; Instructions and instructors in programming tasks; Verbally reflecting;* and *Understanding computational concepts through embodied interaction.*

Instructions and instructors in open-ended exploration

In week 1 of using the toolkit, the instructions were given only verbally. Visual task sheets were provided for the students as a supplement to the verbal instructions, and to enable the students to easily write down their discoveries. The lack of explicit, written instructions was seen to be effective for encouraging open-ended exploration, as supported by evidence of all the students trying out a variety of physical actions (e.g., tilting, shaking, covering, blowing) on the sensors. However, simultaneously, because of the lack of step-by-step instructions, when the students failed to discover a particular effect and got "stuck", the role of the instructor became crucial in enabling them to move forward in the task. Specifically, in these cases, when the instructors noticed that a pair was struggling, they would approach the students, and give them hints about how to proceed with the task, without giving away the answers. Because of the small class size, the students were able to receive help, and quickly continue with the tasks.

Instructions and instructors in programming tasks

In the programming tasks in weeks 3 and 5, written step-by-step programming instructions were provided. These were also supplemented with images showing how the block-based code should look at each step in the ArduBlock programming environment. This was done in order to support the students who had difficulties in reading, and make it easier for the students to self-monitor their progress. It was observed that the majority of groups engaged with the written instructions; these groups read the instructions aloud, and verbally discussed and pointed to where the code should go in the programming environment. This was seen to have helped them to form expectations of what the intended result of the code should be. For example, David and Eric (G2), who discussed the instructions during the "night light" task at length, had an expectation of how their program should function before uploading it to their cube. When asked by an instructor what they thought it should do, before testing it, Eric stated: "*the light will turn on and off, with the light level*". Immediately after uploading the code, he proceeded to demonstrate this by covering the light sensor on the cube, without expressing surprise.

Two groups, however, relied predominantly on the visual images in the instruction sheets (G4 - Teddy and Neil, and G5 – Lily and Gary). Here, instructors played a key role in helping the students to move past 'blocks' in their understanding. For example, when he noticed that they were struggling with the written instructions, one of the key workers helped Lily and Gary by reading the instructions to them out loud. Additionally, these groups who relied on the visual instructions had a harder time understanding what the code represented. For example, the data showed that Teddy did not focus his attention on the written instructions during the "night light" task, and neither read them aloud, nor heard them being read by others. Because of this, it is likely that he completed the task purely by copying the visual representation of the code – without reflecting on how the code worked, or on the concepts instantiated in the task. Once he uploaded the program, he did not understand what the intended effect on the cube should be. At this stage, he required support from an instructor to explain both the program and how it manifested on the cube.

Verbally reflecting

The process of sharing successes and showing off what was accomplished engendered an evident sense of achievement and pride in the students. In addition, it was seen to serve a functional role in probing active reflection. Specifically, when the students shared their successes with the instructors, this enabled the instructors to ask them to explain what they had discovered or programmed. In many instances, this elicited verbal reflection, and enabled them to clarify their understanding. For example, one instructor approached Jason and Keith (G1) during a discovery-based task. Jason quickly said, "*I figured it out. It is movement",* referring to the sensor that caused the light inside the Magic Cube to turn on. He and Keith demonstrated this, by shaking the two cubes at the same time. However, the instructor saw that they were missing a key aspect of the task—that the two cubes were interconnected through Bluetooth, and when both were being shaken simultaneously, the color of the neopixel light was different than when only one was being shaken. The instructor asked them to try shaking only one cube at a time, and then both cubes simultaneously. They then quickly understood the effect, and Jason exclaimed, *"It's going purple! So, the two colors together – they make purple".*

Understanding computational concepts through embodied interaction

The making and discovery-based tasks in week 1 were designed to capitalize on embodied interaction, where the tasks could only be successfully completed by shaking, tilting, and blowing into the Magic Cubes. The first week's session, therefore, enabled the students to build their knowledge by using their bodies to explore concrete examples related to abstract computing topics (i.e., the functionality of sensors and actuators, and connectivity between devices). The students were seen to also use the physical properties of the cubes together to clarify their understanding during the programming tasks in the subsequent weeks. Most groups used the cubes, alongside their code, to iteratively refine their understanding of the programming concepts through "acting out" the code in an embodied way. For example, in the "night light" programming task, Curtis (G3) was unsure if the code he had uploaded was behaving as it was supposed to. The instructor asked him to verbally walk through what his expectations were, based on the instructions he had read. As he did so, he used the cube to physically trace whether the program statement was working as expected. Specifically, as he turned the light sensor side of the cube toward the light, he said *"it turns off"*. He then proceeded to turn it toward the floor, tilting his body toward his partner and saying, "*and now if you point it towards there, it's lighting up… so it makes sense*". Hence, the cubes provided a concrete, physical instantiation of the program through which the students were able to use their existing knowledge of the physical world to test hypotheses and refine their understanding.

(iii) Engagement

The analysis of the students' engagement during the sessions focused on how the learning tasks mediated sustaining and switching of attention and focus during the learning process. These are broken down into the following headings: *Self-paced session structure* and *The relationships between difficulty, enjoyment and engagement.*

Self-paced session structure

The self-paced structure of the sessions was designed to enable the students to proceed with the tasks at their own speed, without having to keep up with the rest of the classroom. This was intended to support the wide variety of abilities in the classroom. The observations indicated that this set up was effective insofar as the pairs progressed at their own pace; some completed the tasks before the session ended, while others did not. Having designed the tasks in a way so that if the students did not complete them all in one session, it did not affect the ability to proceed with new tasks in the following week, also proved an effective strategy. There were no observed instances of students trying to finish a specific task in a hurried way – rather, they were seen to take their time in exploring the interface, and experimenting with their code. Furthermore, not completing a task did not appear to be a concern in terms of the instructor or the students saying anything to this effect.

In addition, the self-paced structure allowed the students to self-regulate their focus on the task. For example, at one point, as Teddy (ASD), was completing a programming task, he seemed uneasy, as indicated by him moving in his seat more than usual, and looking around the room for an extended period of time, without looking at the task-related materials. When an instructor noticed this, she asked Teddy if he would like to start on the next task. He replied that he would not, and decided to take a break from the activity. He chatted with his peers nearby, and went online to look up some tunes. Five minutes later, when a pair sitting next to him started the next task, he decided to resume the task and he once again became highly focused on the programming. The self-paced nature of the tasks, therefore, also enables the students to decide when they need a break from the activities. In Teddy's case, it allowed him to regulate his focus himself, rather than be forced to stay engaged for a consecutive hour and a half.

The relationships between difficulty, enjoyment and engagement

It appeared that the students enjoyed the challenge of completing difficult tasks and were often seen to keep persisting until they had succeeded. For example, in week 1, after the students had assembled the MakeMe cube, they were asked to carry out a difficult task which entailed drawing three-dimensional shapes in the air with the cubes in order to produce various colors of light. It proved challenging for most of the students to get the colors to work. However, the pairs persisted in trying to do this for a long time. They took turns trying to draw the shapes with their partners, and clapped when others around them managed to get the colors to work. The challenging element of the activity seemed to add to the anticipation and suspense of eliciting the intended effects, in turn sustaining their focus. In the peer interviews, several of the students said that this was one of their favorite tasks. However, when it was unclear how to proceed with a difficult task, and where the students became stuck after making considerable effort they would then give up and become disengaged. This happened for the more complex programming activity, in which the students were asked to create an animation. Here, the role of the instructors was integral to getting them return to the task and make progress, by providing individualized support.

9.5 Discussion

Similar to the other studies, the findings demonstrated how the Magic Cubes in combination with the design of discovery tasks, ranging in difficulty, proved to be an effective learning method, but this time when used in a mixed SEN classroom. Beyond this, the findings demonstrated how the Magic Cubes were able to engage students over a period of time longer than one-off sessions, when used with a variety of task types – making, discovery and programming. By using the cubes over a longer period of time in this way, the students in this study were able to not just learn how sensors and actuators work (as in Chapters 7 and 8), but also to think about the contexts in which they can be used in day-to-day life and to learn to program them in creative ways. We found that over the period of six weeks, the Magic Cubes both supported comprehension of computational concepts – such as understanding how IoT hardware works and how to write basic algorithms – and also enabled the SEN students to get excited about learning. They appealed to all the students with different needs and in doing so were inclusive in how they could engender collaborative and engaging experiences. What was remarkable was that many of the students who often find it difficult to direct their attention to a learning task for an extended length of time were able to focus on completing the tasks and to coordinate their efforts with others, by helping, observing and talking about their accomplishments. At times, some students would disengage or take a break from the learning activities; however, they were then able to resume the tasks without too much of a problem, with the help of an instructor, or through their own volition. Next, I discuss the findings in terms of the research questions posed for this study:

RQ 9.1: *Can the Magic Cubes provide an experience that is collaborative, engaging and supports comprehension, for a spectrum of learners in a typical SEN school setting?*
RQ 9.2: *What difficulties do learners with SEN face when interacting with the Magic Cubes? How are these overcome?*
RQ 9.3: *What kinds of informal methods of evaluation are appropriate for assessing the students' experiences and learning?*

RQ 9.1: Can the Magic Cubes provide an experience that is collaborative, engaging and supports comprehension, for a spectrum of learners in a typical SEN school setting?

As demonstrated by the teacher and peer interviews, together with the analysis of audiovisual data, the sessions with the Magic Cubes were able to positively engage students with a wide variety of abilities, and over a period of six weeks. To address in more detail how this was achieved, I discuss what the observed interaction patterns from the sessions tell us about supporting collaboration, engagement and comprehension in a SEN classroom.

Collaborative learning

One form of collaboration that took place was through visible 'waves' spreading throughout the classroom, where the SEN students observed each other's accomplishments when interacting with the cubes, and then tried for themselves the successful physical actions of others. Similar to the findings of the previous studies, it seems that the visibility of interacting with the cubes accompanied with much evidence of excitement and demonstrating to others after discovering the sensor-effect mappings, played an integral role in how the students collaborated when learning about computing. In particular, when completing the physical tasks with the cubes that did not require using a computer screen, much collaboration both *within* and *between* pairs was observed, where the students were seen to learn together by watching and mimicking others around the classroom.

While the students collaborated *within* their pairs/groups for all of the learning activities, it was found that they needed to be explicitly instructed to collaborate *between groups* when using the computers during the programming activities. In some ways, it is to be expected that less between-group collaboration would occur when the students were programming, as the digital code appearing on their computer screen is harder to see by others, compared with the physical actions when using only the cube in an open physical space (e.g., on a table). The screen constrains who can observe what others are doing when solving a task. Also it is much harder to talk about the code being written than show and talk about effects that are clearly visible on a cube.

However, when a pair was explicitly asked to help another out during the programming activity, they did so, by discussing at length their trial and error processes when programming. They were also able to give each other feedback on what might be going wrong in the code. This seemed to be a positive experience for both pairs involved: the pair that was *receiving the help* was able to get support from someone who understood why they were having a problem and explained how to proceed in a way that was easy to understand; for the pair that was *providing the help*, in turn, the experience enabled them to reflect on what they themselves had learned through the programming activity. Together, a question these findings raise is whether this kind of peer support should be encouraged more when programming, which can help students to proactively problem solve together, rather than always asking for help from a teacher. This corroborates with previous research on teaching computing in SEN settings that promotes explicitly teaching students to seek help from each other before asking an instructor [Israel, Wherfel, Pearson, Shehab, & Tapia, 2015].

Sustained attention and pace of learning

Another unexpected finding was that most of the students were able to sustain their attention when working on the tasks for extended periods of time, and that this persisted over the period of six weeks. This surprised the classroom teacher who remarked how often some of his students find it difficult to keep focused and pay attention throughout classes. While the novelty of the Magic Cubes played a role in contributing to the unexpected high levels of engagement, it is also the case that other factors were instrumental, including: the design of both engaging and challenging learning activities that on completion enabled the students to share their sense of achievement with others; the self-paced design of the learning tasks, that were able to avoid anxiety from materializing about completing in time; and the availability of appropriate kinds of learning materials and informed instructors at hand.

Although previous research has suggested that clearly structured learning activities may be more appropriate for students with learning difficulties [Falcão & Price, 2010], we found that the open-ended and self-paced design of learning tasks in our intervention was, in large part, effective in promoting inclusive learning for a variety of abilities and needs. This provided more flexibility for children with special education needs, who can have different attention spans and may become easily distracted. In particular, it allowed for them to decide at which speed to complete the tasks, and when to take breaks when they had had enough – which in turn fostered more sustained engagement over the whole of the session. Moreover, using shorter tasks in the sessions, designed at different levels of complexity, meant that there was no time pressure on the students to finish at the same time as others. In addition to reducing stress on the students, this enabled the instructors to provide targeted and individualized support to small groups of students when needed, rather than constantly addressing the class as a whole and working to ensure all were simultaneously at the same point in the tasks. Where typical SEN classrooms usually have small class sizes and more than one instructor, it seems that this strategy of using short, self-regulated tasks in interventions can carry over to other interventions in SEN.

A potential downside of adopting a self-paced approach for mixed SEN classrooms, however, is that some children may feel left behind while others progress at apace. Also if one partner becomes disengaged during learning, it can be difficult for the other to figure out what to do. In our study, this did not seem to be a problem, as when a partner in a pair withdrew for a while, the other carried on without them or joined another group. We saw this in the example when Neil had checked out, and his partner Teddy quickly joined another pair or carried on by himself. The students were also able to switch straight back into the task again, seemingly without feeling they had missed out or that they were behind in progressing with the task.

More generally, the observed differences between students' collaborative interactions and their ability to focus on the discovery-based and programming tasks demonstrate the importance of considering how a student's ability to interact and engage can change depending on the type of task they are being asked to do and the technology/learning materials they are provided with. Other studies have also noted how physical and tangible interfaces can foster higher levels of collaboration (e.g., [Horn, Solovey, Crouser, & Jacob, 2009]). However, these effects are often attributed to the form factor of the interface itself, without a detailed explanation of the effect of the set up of the learning environment and the associated materials on interaction. Our study suggests that the way the classroom is set-up and whether the students are sat in front of a PC computer, can significantly impact the extent to which they will engage in collaborative learning. Moreover, providing a toolkit by itself is not enough; the context of its use and how it can be designed to be inclusive is equally critical. This is especially important to consider for SEN settings, where the children are likely to have varying needs, based on their ability to focus for extended periods of time, type of disability, mobility, level of vision and hearing impairment, and so on.

Embodied learning to support comprehension

Supporting mental "debugging" through embodied actions has long been suggested to assist learning, stemming back to Papert's turtle Logo, in which children programmed a physical turtle to learn geometry concepts [Papert, 1980]. Our findings corroborate with earlier research, where it has been suggested that kinesthetic and embodied interactions are important for helping students with intellectual disabilities to learn [Falcão & Price, 2010; Israel et al., 2015]. In our study, it was the combination of being able to manipulate a physical cube while coding that enabled the students to carry out a form of embodied debugging which supported their comprehension. Specifically, they used the cube to move between abstract code and the concrete representation of what the code represented. For example, after uploading the code when coding the "night light", the students were seen to reach towards light sources and hide the cube under a table as a way of making sense of the abstract programming constructs in specific lines of their code. These types of embodied interactions were contingent on the ability to hold a Magic Cube in the hand, and then carry it and manipulate it in 3D space. This suggests, likewise, that physical computing activities can facilitate learning about abstract functionalities of sensors, actuators, and about programming constructs, through enabling the students to enact them out. Next, I return to the second research question posed in this chapter.

RQ 9.2: What difficulties do learners with SEN face when interacting with the Magic Cubes? How are these overcome?

The findings identified a number of difficulties that the students with SEN faced when using the Magic Cubes, together with the strategies they used to overcome them. In particular, there were a number of instances where the students struggled with the learning activities, for reasons related to their cognitive and physical difficulties. However, they were often able to overcome these through the support of their peers with whom they were working in pairs/groups – for example by one partner in a pair taking the lead on a task that the other found difficult. We also found that in some cases, some activities were better suited to promoting inclusive participation and learning than others. In particular, the discovery-based tasks, where it was easier to observe what others around the classroom were doing without sustaining consistent joint attention and which had a lower threshold point for collaborating, enabled a student on the more severe side of the Autism Spectrum to participate more easily and for a sustained period of time.

Another aspect of inclusive design that was considered important was to provide instructions appropriate to the different needs. A mix of verbal, visual and written instructions was found to be a good combination that the students could select and access, depending on their abilities and strengths. However, the students who relied on the purely visual, step-by-step instructions—such as photos representing the intended code structure in the programming tasks—appeared to reflect less on what was *being done* than those who used the written and verbal instructions. This suggests that different representations of instruction materials differ in terms of how informative they are and how well they can cognitively engage the learner. In particular, when the students relied purely on the visual instructions, they were able to complete the tasks but then often did not understand the effects embedded in the cubes. It is apparent that in these instances, simply following the instructions was not sufficient to cognitively engage them with the computing concepts underlying the learning activities.

This calls into question how to ensure that instructions for programming tasks can be designed to be sufficiently supportive for SEN students, while ensuring that students are prompted to step away to reflect on what they are coding. Previous literature suggests that balancing explicit instructions with open-ended enquiry can be a useful strategy for ensuring reflection [Israel, Pearson, Tapia, Wherfel, & Reese, 2015]. Our research has also shown that there needs to be more consideration given to the specific special needs of each child, to enable both discovery and reflective learning to occur in a way that suits them. However, this needs to be offset against the needs of enabling children to be paired up with others to be able to reap the benefits of learning and sharing with each other.

RQ 9.3: What kinds of informal methods of evaluation are appropriate for assessing the students' experiences and learning?

Employing a number of informal methods was found to be effective at enabling students with SENs to reflect on their learning while at the same time at gauging how successful the classroom activities had been. Asking the students to make slide presentations allowed them to reconstruct what they had learned in an enjoyable away, rather than as a test of their knowledge that could be viewed as stressful. The design challenge was also seen as a creative exercise with many providing innovative and original ideas for how they could use sensor-based and IoT technologies in their own lives. In terms of the peer interviews, these were found to be informative in terms of revealing what the students enjoyed most and found difficult – which could then be tied back to the design of the learning tasks. On the other hand, the peer interviews were not useful for gauging comprehension at a nuanced level, because the students only talked about the broad topics that they had learned about, for example saying that they had learned to make animations, or that they had learned what sensors are. To make the interviews informative in terms of how much the students had learned, it might have been useful to add more detailed questions that dealt with comprehension, for example by asking the interviewee to present a piece of code to the interviewer and describe what it does (see [Portelance & Bers, 2015]).

In sum, the extent to which these three methods were informative about the different aspects of the learning experience varied, suggesting that using a combination of methods rather than relying on one is preferable in order to get a picture not only of what they had learned but also how they learned. While the analysis of the audiovisual data was very informative and allowed us to qualitatively analyze the learning processes, the reflections generated by the students also provided valuable insights about what they found easy, difficult, enjoyable and frustrating.

The methods used therefore provided a richer picture than scores that are conventionally used to test school children for their knowledge. For children with SENs it can be difficult and considered undesirable to ask them to do a test, causing undue stress. In contrast, we argue that using informal methods that ask them to generate different kinds of content that can be presented to others, along with the use of peer interviews is a far more valuable assessment method, enabling SEN students to reflect on their learning. This type of mixed methods approach can be informative in terms of evaluating the extent to which the learning activity is appropriately designed, while contributing positively to the overall experience of the intervention. In the future, new kinds of metrics may be able to be extracted by triangulating the outcomes of these qualitative methods that will allow teachers to generalize across different classes.

9.6 Summary

There can be many challenges for supporting learning in SEN classrooms, especially for abstract topics like computing. Students often have a wider mix of abilities than their peers in mainstream schools, and it can be more difficult to plan lessons that provide engaging and effective learning experiences for all. However, as our study has shown, the affordances of employing physical computing interfaces like the Magic Cubes shows much promise for SEN classrooms, especially when the design of the task type and supporting materials enable self-regulated, embodied learning with appropriate support from the instructors. If tasks are designed in this way, physical interfaces can enable students with a range of special education needs to leverage their abilities to collaborate and engage with curricular content, while fostering comprehension, enjoyment and a sense of self-accomplishment. Hence, there is much scope for designing these kinds of technologies to support more inclusive computing education.

CHAPTER 10: APPROPRIATING LEARNING ACTIVITIES FOR A PUBLIC OUTREACH CONTEXT

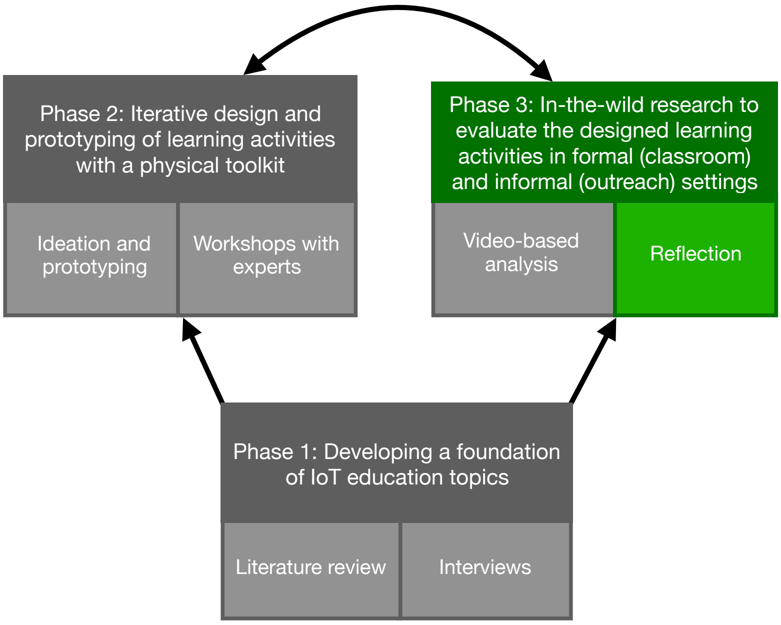


Figure 10.1: This chapter reflects on deployments of the Magic Cubes in informal learning contexts, in order to investigate how learning activities designed for teaching computing in the classroom can be adapted to best effect for a diversity of public outreach settings.

The research presented in this thesis so far has been concerned with using the Magic Cubes to teach children about computing and IoT in classrooms, within their school day. However, learning about computing does not need to be constrained to classroom contexts; informal settings can also be a great means of sparking children's curiosity in a subject and driving interest in further learning. Learning in informal settings – ranging from festivals to after school activities – can also be a way for children and teenagers to try out new technologies, that schools might not be able to bring into the classroom. Moreover, informal settings can be a means of reaching more diverse audiences. For example, as opposed to teaching a specific school year in a classroom, outreach contexts like computing festivals often bring children of all ages; meanwhile, events at festivals and museums can also provide opportunities to engage with whole families. The Magic Cubes were envisioned as a tool for both for formal and informal settings. A question this raises is how to design learning activities for both, given their different demands.

Designing learning activities for informal settings requires different considerations than designing for the classroom (see e.g., [Hall & Bannon, 2006; Lakanen, 2016]). For example, at museums and festivals, visitors are free to come and go as they please, and therefore learning tasks have to be designed in a way where even a short interaction of a few minutes can leave the visitor with a new insight. In structured outreach sessions which can last from a half hour to a full day, there is more scope to design learning activities that last longer and where more of a topic can be explored. Children attending these organized events are likely, too, to have different expectations than in a classroom context. A key research concern is whether taking part in an outreach session, such as a hackathon, a coding workshop or a museum exhibit will spark an interest in that topic, especially computer science, later on or that can be followed up at home. However, this is difficult to determine, other than anecdotally, as it can be some time before a long-term interest materializes. For this reason, following the long-term impact of informal learning is out of scope for this thesis, and instead this chapter only reports on participants' experiences with the Magic Cubes during informal learning sessions.

Throughout this research, a number of opportunities arose to use the Magic Cubes in informal learning contexts. These ranged from drop-in sessions at museums and festivals geared to wide audiences, to structured sessions at pre-university programs and after school coding clubs. For each of these events, the research question was how to design the learning tasks using the Magic Cubes so that they could be adapted to suit the context, and made appropriate for a more diverse audience than a specific age group at a school. This chapter describes how learning activities were designed for various outreach events, and the extent to which they were successful in instilling excitement, curiosity and intrigue in the children who took part in them. It ends by discussing the insights gleaned about how new tools for teaching computing can be appropriated in informal learning contexts.

10.1 Motivation and Research Questions

Computing is increasingly taught in settings outside of the classroom. For example, many primary and secondary schools now have after-school, volunteer-run computing clubs for children interested in learning to code. In addition, consumer educational toys, like those created by Tech Will Save Us [Tech Will Save Us, n.d.] enable families to explore coding and physical hardware together at home, through sensor-enabled DIY kits for making, for example, solar powered plant water sensors and light-up bike wheels. Moreover, national museums in the UK are holding an increasing number of technology-oriented exhibitions that include family days with hands-on activities and workshops, such as the Barbican's 2019 "AI: More Than Human" exhibition[5], and the Science Museum's 2018 "Robots" exhibition[6].

As well as getting children to experience computing in a new way, teaching computing in these contexts is important for a pragmatic reason. Specifically, buying the newest technology and software is often out of budget for schools [Harbird, Barbareschi, Makrygianni, Holloway, & Hailes, 2017], and as such can exclude many schoolchildren from experiencing new advances in computing. This is an especially large barrier for technologies that include physical hardware, which are more difficult to make free or affordable, compared with computer software. For these reasons, when designing new technologies for teaching computing, it is important to envision them being used in contexts that extend past the classroom – such as after school clubs, computing festivals, and even at home.

However, the context of informal settings can be very different to classrooms, potentially changing the way people interact with the technology. For example, children may be working together with their families, or peers who they have never met before, rather than their classmates with whom they are used to learning, which can change how collaboration unfolds during an activity. Moreover, the learning design principles developed by Rusk, Resnick and Cooke [2009] and the research of others in this area (e.g., [Harbird, Barbareschi, Makrygianni, Holloway, & Hailes, 2017; Lang, Craig, & Casey, 2017; Lyons et al., 2015]) suggest that the design of the learning

5 https://www.barbican.org.uk/whats-on/2019/event/ai-more-than-human

6 https://www.scienceandindustrymuseum.org.uk/what-was-on/robots

activities and materials alongside the software/hardware is critical. For example, if the activities are designed to be too easy, children can lose interest. If they are too difficult the children may give up too easily. Key is to design them to be both accomplishable but challenging.

Another difference between classroom settings and some informal learning environments (for example, museums or festivals) is the freedom of choice about whether or not to interact with an exhibit or technology. As opposed to classrooms, where students are assigned tasks that they are expected to complete, in many informal environments, visitors face an array of choice for what to see and try. Moreover, visits can range from quick, minute-long interactions, to extensive explorations of a displayed artifact [Hall & Bannon, 2006]. These considerations bring the need to be mindful of how to attract visitors, for example when exhibiting a technology at an event with many parallel exhibitions, as well as how to design for both short, transitory visits and for visitors who become interested and want to learn more. Previous research on science exhibitions in museums, for example, has stressed the importance of: considering how to make the space in which a technology is exhibited inviting; providing a variety of activities to support different levels of interest; and providing opportunities for open-ended exploration and discovery [Hall & Bannon, 2006]. Other researchers have also stressed the importance of providing sufficient information about the exhibited technology so as to enable the visitor to easily get started with discovering how it works, without being completely prescriptive as to how they should interact [Lyons et al., 2015].

The purpose of informal learning environments is also often distinct from that of classroom learning. In the classroom, there is usually an expectation that learning is to take place; in informal environments, visitors may come for fun, to relax or to gain new experiences [Paris & Hapgood, 2002]. This means that learning activities are often designed with a more central focus on enjoyment. Learning in informal environments is also not necessarily measurable, and may lead to more of an implicit impact, such as a new awareness of a topic, than to direct learning outcomes [*ibid.*]. This suggests that in these environments, giving an overview of a topic and provoking curiosity is more important than conveying specific learning outcomes.

Together, these differences between classrooms and informal learning environments raise the question of how to best engage the visitors who come to outreach events with the Magic Cubes, in different kinds of informal learning settings? In this chapter, I address this question in three parts:

> ***RQ 10.1:*** *What factors need to be considered when designing learning activities for using the Magic Cubes for a diverse set of visitors in informal settings?*
> ***RQ 10.2:*** *How to determine what kind of experience visitors have in these informal settings, whether they spend a short time with the Magic Cubes or a longer period of time?*
> ***RQ 10.3:*** *What types of facilitation and instructional materials to provide to guide visitors when first encountering the Magic Cubes in informal settings?*

10.2 Evaluation of the Outreach Sessions

The outreach events throughout this research were held in a diversity of settings (for the full list of sessions that were carried out, see Appendix C). The particular events that are described in this chapter are for those where children (predominantly aged 6-12) and teenagers made up a majority of the audience. The outreach events that were run, where mostly adults participated, without children present (for example, UCL alumni events, and interactive demos at scientific conferences) are excluded here.

The main goal of this chapter is to see whether and how the learning activities that were initially developed for use in school settings (as described in the previous chapters) could be adapted for a variety of informal settings, to engage visitors and provoke their curiosity in learning about computing. The nature of the session was intended to be one where they could try the Magic Cubes out, as a taster of what is entailed in physical computing. In these settings, the emphasis was more on reflecting on how the children and other visitors used the cubes in situ rather than reflecting on what and how they had learned.

The methodological approach adopted for evaluating the sessions was also informal, based mainly on my own observations and reflections of how the Magic Cubes were used in the outreach settings for the adapted learning activities, rather than on direct data about visitor interactions. The reason for this is that during the outreach events that were carried out, the process of gathering data about visitors and getting consent for data collection was considered both infeasible and off-putting to the visitors. Specifically, for many of the drop-in events at museums and festivals, the visitors interacted with the Magic Cubes in high volumes, and often only for a few minutes each. Therefore, it was not possible timewise to ask visitors for consent to collect data about them; also, it may have discouraged many from participating. It would also have been detrimental to me, as a facilitator, in terms of distracting me from observing the environment and reflecting on how the visitors were interacting with the technology. In turn, at more structured extracurricular events where children and teenagers interacted with the Magic Cubes for a longer period of time, due to the organizations we were working with, we were not able to ask the children's parents for consent to gather data about them ahead of the sessions. During these events, the children were unaccompanied by parents, and therefore getting the parents' consent to gather direct data was not possible.

Therefore, in the outreach events described in this chapter, no data was directly collected about the visitors and participants. Instead, after each event, I wrote reflective notes about how the event unfolded and made anonymous observations about how the visitors interacted with the Magic Cubes. These specifically focused on which activities were found to be more or less engaging, disengaging or difficult, based on observations of how people interacted with them and the types of problems that arose. They also focused on the challenges that were found with running the activities in different contexts. Moreover, the focus of the observations was not just reflective but also reflexive. Specifically, in the notes I also considered how I led the sessions and the issues that I faced in different contexts. These types of reflections included, for example, instances when I felt that I did not address visitors' questions sufficiently, or when I became overwhelmed by the flow of people, and why this happened.

Finally, the findings described in this chapter also include quotes from two semi-structured interviews from experts in computing education and public outreach working at UCL to obtain perspectives from those who have had much experience in designing and running outreach programs. Specifically, the individuals who were interviewed are: Elpida Makrygianni (referred to as EM), who is the UCL Engineering Engagement coordinator, and Rae Harbird (referred to as RH), who is a Teaching Fellow in Computer Science, and is heavily involved in public outreach. These two individuals were present (without direct involvement) at a number of the outreach events where the Magic Cubes were used. The reason for carrying these interviews out was as an additional source of feedback about what worked and what did not. During the interviews, beyond reflecting on the Magic Cubes specifically, both interviewees also provided insights about structuring outreach sessions effectively, and at a general level, how public outreach can play a role with overcoming the barriers that face primary and secondary computing education; some of these are reported on in this chapter.

In sum, the findings reported in this chapter are a synthesis of my and two interviewees' reflections on how the Magic Cubes can best be used in a variety of contexts. This synthesis is then used to derive considerations for designing learning activities with a physical toolkit, for a diversity of informal settings.

10.3 Outreach Settings and Learning Activities

The events that are included in this chapter are broadly broken down into two categories. The first is *drop-in events for diverse audiences* at museums and festivals, where most interactions were short, lasting up to 5-10 minutes. The second is *structured extracurricular sessions for children and teenagers*, which lasted for between 30 minutes and 3 hours. Next, I describe each of these categories in more detail, and provide examples for each together with a description of the types of activities with the Magic Cubes they included, and our considerations when deciding what activities to bring to each.

10.3.1 Drop-in events for diverse audiences

These types of events were held at museums and computing festivals. For each of these events, the Magic Cubes were presented at a table or stand, which visitors could freely walk up to. In each of these types of events, there were numerous similar stands distributed throughout the space showcasing other interactive technologies or exhibitions. The audiences at these events varied; at computing education festivals, the audiences included mainly children in primary and early secondary school accompanied by their teachers; in turn, at museums they included mainly families with children. To illustrate this category, I provide two different examples, and discuss how the activities with the Magic Cubes were adapted for the visitors to each event. These are the *Computing Celebration at Emirates Stadium,* a computing education festival, and *The Science Museum Year of Engineering Festival,* a festival held for the public at a large national museum.

Computing Celebration at the Emirates Stadium

This event was aimed at celebrating the computing education achievements of London's Islington Council schools. The main focus of the event was on children from both primary and secondary schools, bringing in their own computing projects to showcase to each other and other attendees. Groups from universities and industry – including our group from UCL – were also invited to showcase new technologies designed for supporting computing education. The children and their teachers who attended the event were given time to explore the many stands that were showcasing the technologies, during 20-minute slots. Over the course of the day, approximately 100 visitors, all of whom were children and teachers, visited the Magic Cubes stand.

Adapting activities with the Magic Cubes for this context

Because we knew each school would only have a limited amount of time for each stand, we adapted the learning activities with the cubes so that they could be completed very quickly. Many of the teachers that attended the Computing Celebration were also interested in trying new types of computing education technologies that could be integrated into their classrooms, and learning more about how they could tie new technologies into their curriculum. To this end, the activities were selected to give the visitors an idea of what the Magic Cubes and physical computing technologies in general, could do. Therefore short, discovery-based tasks were deliberately chosen as the activities to demonstrate. The importance of providing immediate 'digital' feedback after conducting a physical action was a key feature of the activities selected, so the visitors could readily make a connection between their actions and what effects they caused. They included a version of the Color Mixing activity (discussed in detail in Chapter 6), where two cubes were connected through Bluetooth and visitors could "pour" color from one cube to another. Other cubes were pre-programmed with the discovery-based tasks described in Chapter 7, where physical actions led to a digital effect in the cube (e.g., blowing hot air into the temperature sensor caused the animation on the cube to change). Because they included flashing lights and required physical actions to elicit digital effects, these activities also had the added benefit of being visible from a distance, which was hoped to draw visitors to the stand. In addition, one laptop was also brought, and a short worksheet was provided where visitors were able to change a single line of code on the computer in order to change the color of light inside the cube. This was so as to show the children how code can be transferred from a computer to a physical device, and to show teachers the programming environment used with the Magic Cubes.

The Science Museum Year of Engineering Festival

We were invited to hold a drop-in session with the Magic Cubes at the Science Museum in London, over a period of two full days. The visitors were predominantly families with children of all ages, who were attending the Year of Engineering festival to help their children develop a curiosity about computing and engineering, as well as to support their children's existing interests. Over the course of the two days, approximately 250 attendees visited the Magic Cubes stand.

Adapting activities with the Magic Cubes for this context

For this event, we anticipated that visitors would be on less of a schedule, and therefore some visitors would have more time to interact with the Magic Cubes, compared to the Computing Celebration described above. For this reason, both the short, discovery-based activities were provided, and in addition, longer coding activities than above, that were expected to take visitors about 5-10 minutes to complete. Because we anticipated a wide range of visitors, including children as young as 5 years old, we also devised a range of activities that would appeal to different audiences.

We set up a stand for discovery-based tasks with the Magic Cubes, as well as a long bench with 5 laptops, where visitors could try coding the cubes themselves. On the table, we displayed a variety of discovery-based activities. To engage younger children, aged below 9 years old, we pre-programmed some of the cubes so that the LED matrix displayed the numeric light sensor reading from the cube in real time. Young children were given the challenge of finding the darkest and lightest places in the exhibition hall. For another activity, we connected a galvanic skin response (GSR) sensor to the cubes, and provided a worksheet for visitors to work through (based on the field journals described in Chapter 8), which asked them to reflect on when and why sensor values dropped and when and why they became higher, for example, in the context of telling lies.

For the coding activity, a shorter version of a programming activity that was used in the SEN study (Chapter 9) was devised, that guided participants through making the cube into a "night light," in which the light inside the cube turned on when the cube's light sensor sensed darkness. We also devised some more complex programming activity sheets, and provided the documentation of the Arduino libraries developed for the Magic Cubes, for visitors who had more programming experience.

Hence, the learning activities and accompanying materials were adapted for this context to suit both short and longer visits, for families with children, and for those with either no experience or some experience of computing.

10.3.2 Structured extracurricular sessions for children and teenagers

The longer extracurricular sessions that were run were organized in collaboration with external organizations; these included for example, the Royal Institution[7], CodeWeek UK[8] and local programs for teenagers with an interest in coding. These sessions varied widely in terms of different audiences. Some were attended by primary school children, who came in groups with classmates from school; others were attended by teenagers

[7] https://www.rigb.org/education/masterclasses
[8] http://codeweek.uk/

aged 12-14 years old, who had an existing interest in engineering and computing, but did not know each other before the sessions. Moreover, because of the focus of the programs run by the external organizations, which the sessions were a part of, was on teaching programming, these sessions focused in large part on teaching coding using the Magic Cubes. Therefore, the discovery-based learning tasks were used as introductory activities and the majority of the time was spent showing the children how to program the sensors and actuators in the cubes. To illustrate what happened in this category of outreach, I provide two different examples of structured sessions: the *CodeWeek UK Launch*, a large event where primary school children attended a variety of 30-minute coding workshops, and the *Engineers Save Lives Masterclass*, where thirty 12-14 year olds participated in a 2.5 hour session.

CodeWeek UK Launch

The CodeWeek UK Launch in London is an annual event for approximately 200 primary school students. In the event, numerous organizations run structured 30-minute workshops to teach the children different aspects of computer science and coding using new technologies. We were asked to run three of these workshops over the course of the day, with ten 9-10 year olds in each workshop. The children who attended came with their school groups, and so knew each other prior to the session.

Adapting activities with the Magic Cubes for this context

The age group for this event was the same as that in much of the empirical work that was carried out in classrooms throughout the thesis. However, because the workshops were shorter in length - only 30 minutes as opposed to the 60-90 minutes for each class session - we adapted the activities from those used in classroom sessions to be more condensed, so as to provide an overview of the functionality of the Magic Cubes but also to enable the children the opportunity to experiment with coding the cubes. The adapted activities involved the children being asked to explore the data in their environment by using the Magic Cubes to measure light levels (as in Chapter 8). Based on this, they were then provided with a short step-by-step instruction sheet to program a night light, which measured the amount of light in the environment and turned the neopixel light in the cube on and off accordingly (as in Chapter 9). Hence, the adaptation here was to condense the topics that were previously designed for 60-90 minute sessions in classrooms, into a shorter period of time.

Engineers Save Lives Masterclass

This event was held for thirty 12-14 years olds whom we knew already had some experience with coding. Moreover, although most of the participants had only previously done programming in school, all of the participants at this event were selected for their interest in computing and engineering. Therefore, the coding activities could be designed knowing they had had some previous experience with programming. The session was 2.5 hours long, which also meant that in contrast to the previous category, there was much more time than in the sessions designed for classrooms.

Adapting activities with the Magic Cubes for this context

Because this session was much longer than any of the others, considerable thought was given as to how to fill the time so that the children had a sense of accomplishment without getting frustrated or bored. To this end, all of the discovery-based activities that were designed for the classroom study on critical thinking (presented in Chapter

8) were provided, together with other coding activities. Specifically, the children were asked to explore how different sensors in the cubes worked (e.g., light sensor, temperature sensor, GSR, pulse sensor) by measuring data from their environment and their bodies. There was also an emphasis in the session design on supporting the children – who largely did not know each other prior to the session – in getting to know each other, before working only in pairs for the coding. Specifically, it was hoped that the discovery-based tasks would lead to the same collaborative behavior in the room, as that observed in the classroom studies, and that this would help the children get to know each other and feel comfortable in the new environment.

For the remainder of the session – lasting about 1.5 hours - programming activities were provided for the children to work in pairs using the Magic Cubes. Three programming activities were designed that were assumed would fill the 1.5 hours, with each building on the previous task, in terms of the coding and physical computing constructs it aimed to teach (e.g., if-else statements, for loops, Bluetooth). The children were encouraged to go at their own pace, so that there was no pressure to finish all of the activities. Hence the adaptation for this category was to extend the activities to fill a much longer session.

Table 10.1 provides a condensed summary of the needs and constraints of the different events described in this section, and the adaptations made to the Magic Cubes activities, together with the rationale behind these adaptations.

Table 10.1: Summary of the four representative Magic Cubes outreach sessions described in Section 10.3, highlighting their differences and the adaptations made.

Event name: Computing Celebration at the Emirates Stadium **Type:** Drop-in event for diverse audiences **Audience:** Primary and secondary school children & teachers **Needs and constraints:** • The visitors had a short amount of time to interact with each stand • Many parallel stands, leading to a need for activities that attracted visitors' attention **Goals of the session:** • Provide an overview of the Magic Cubes • Spark children's interest in physical computing • Provide teachers with information about new physical computing tools **Adaptations made to structure of the session:** • Presented only tasks that required no prior experience with physical computing • Focused on short, discovery-based tasks that could be completed in a short amount of time
Event name: The Science Museum Year of Engineering Festival **Audience:** Families visiting the Science Museum together; children of all ages **Needs and constraints:** • Varied age groups, including children as young as 5 years old and adults • Variability in: amount of time to interact, interest levels and attention spans **Goals of the session:** • Provide an overview of the Magic Cubes • Spark visitors' interest in physical computing • Allow individuals with pre-existing interest and experience with physical computing to explore the Magic Cubes more creatively and in depth **Adaptations made to the structure of the session:** • Provided a range of discovery-based tasks for different age groups • Additionally provided a range of simple to complex coding activities, varying in length
Event name: CodeWeek UK Launch **Audience:** Groups of ten 9-10 year old children with little to no coding experience **Needs and constraints:** • The emphasis of the event was on coding; the children had little to no coding experience • Only 30 minutes allotted with the Magic Cubes • Despite this, a need to provide the opportunity to engage with coding in a meaningful way **Goals of the session:** • Introduce the children to sensors and teach how a sensor can be controlled through code • Demonstrate how code can be transferred onto a physical device **Adaptations made to the structure of the session:** • Begun with discovery-based tasks • Asked children to program a "night light" using the knowledge they had gained about the light sensor in the discovery-based phase • Provided a step-by-step instruction sheet to minimize time spent on trial and error
Event name: Engineers Save Lives Masterclass **Audience:** Thirty 12-14 year old children, with at least some coding experience **Needs and constraints:** • The emphasis of the session was on coding • The children did not know each other prior to event, creating the need to build a welcoming atmosphere to help them get to know each other and collaborate • Ensure activities were long enough to keep them engaged for 2.5 hours **Goals of the session:** • Introduce sensors and teach how a sensor can be controlled through code • Demonstrate how code can be transferred onto a physical device • Provide activities at the right level to engage children with both little and more experience coding **Adaptations made to the structure of the session:** • Provided a variety of discovery-based tasks to encourage icebreaking and collaboration • Provided creative programming activities, ranging from simple to more complex • Provided a self-paced structure so that there would be no pressure to complete all activities

10.4 Reflections on the Efficacy of the Sessions

The reflections on the efficacy of the sessions are structured in terms of: those from drop-in sessions; those from longer extracurricular events for children and teenagers; and high-level ones on using public outreach to support computing education. The reflections are based on my notes and impressions from the sessions. First of all, it was noted that the format and task adaptations worked very well for the various informal settings. In particular, the Magic Cubes together with the adapted activities, were found to be successful in playfully engaging a diversity of audiences, beyond those which were the focus of the school studies – including children as young as four years old, parents and children interacting together and even teachers – showing just how universal the appeal of learning physical computing with the Magic Cubes was. The

Magic Cubes were also observed to facilitate a range of collaboration similar to that observed in classrooms, for example, helping children who had never met before get to know each other by interacting together. Furthermore, in each session, the Magic Cubes were seen to spark many visitors' general interest in physical computing – with many asking where they could buy the Magic Cubes, and for recommendations for other toolkits to try — including teachers in schools and parents wanting to get their kids more involved with computing. However, a number of difficulties were observed during the outreach sessions. These included not being able to provide individualized support when facilitating sessions alone with large groups of visitors, and managing how much time visitors spent interacting with the cubes, in order to enable everyone to have a go. These are later discussed as design considerations for planning for sessions in varied informal learning environments.

10.4.1 Reflections from the drop-in sessions and further adaptations made

The observations made from the drop-in sessions are described in terms of *(i) drawing in visitors through the Magic Cubes' high visibility and low threshold to interaction*, *(ii) adapting the activities to enable varied interactions*, *(iii) tensions of facilitation and time constraints with multiple visitors* and *(iv) fostering visitors' wider interest in physical computing.*

(i) Drawing in visitors through the Magic Cubes' high visibility and low threshold to interaction

Across the various drop-in events, it was observed that the Magic Cubes consistently attracted passers-by who were standing or walking nearby. The affordances of the cubes made them highly visible from across the room and this caught many visitors' attention. Specifically, at each event, we set up the cubes on the table so that some flashed colorful lights, and others showed dynamic animations. This may have contributed to the cubes' visibility as well as the visitors' curiosity to approach the stand. Moreover, at drop-in events, a honeypot effect [Rogers & Brignull, 2002] was consistently observed. By this is meant, when one or a group of visitors started interacting with the cubes, and more people would come to see what was happening. In other instances, children visited the stand alone and completed the activities, then left and came back with their friends or families to show off what they had explored and to encourage them to also try them. These observations were corroborated by EM, who noted during the interview that during drop-in events, *"there were other sessions there happening in parallel, and even within our stand, there were other departments featured. But the Magic Cubes was the one that was attracting all of the children."* EM attributed this to how immediately interactive the Magic Cubes, pre-programmed with discovery-based tasks were, in relation to other computing toolkits that take more effort to begin using, *"because it is so visual and so interactive, and it's immediately something that you can play with, you can interact with dynamically."* Hence, the high visibility of the Magic Cubes, coupled with the low threshold to interacting with them, was key to their effectiveness in informal, drop-in settings.

(ii) Adapting the activities to enable varied interactions

The short, discovery-based tasks and having one or two laptops on the same table, which visitors could use to quickly change a line of pre-written code and upload it to the cube, also helped visitors get started with writing code and learning how the Magic Cubes interface with a computer. However, over time, I noticed that in events where audiences were not time constrained, there were always visitors who lingered, wanting to experiment with the Magic Cubes in a more open-ended way, but who were limited by the short tasks that were set.

Therefore, for the next events, I began to set up more diverse tasks that could support both transitory interactions, and longer explorations of the Magic Cubes. I also realized that for longer visits, standing at a table to program the cube was not ideal. This was because other visitors would crowd around the table to talk to me and other facilitators, impeding the visitors who wanted to code. Therefore, where possible, I began to set up a separate coding area, where visitors could sit down and have a longer interaction.

Furthermore, at events where there were varied audiences, I became attuned to the different needs of young children, teenagers, and families. For example, younger children were always excited to explore the cubes, but largely ignored written instructions, and often became distracted if an activity required a long explanation. I also found that families seemed to most enjoy activities they could playfully engage in together. These observations informed the final outreach session held at the Science Museum. Specifically, for young children, an activity was set up similar to that in the Chapter 8, where visitors were provided with a cube programmed to display the light sensor reading, and asked to find the brightest and darkest places around the room. This enabled young children (in some instances, as young as 4 years old) to take the cube in their hands and run around the exhibition hall space probing different light sources, often while their parents and older siblings spoke to me about other activities. An activity which appealed especially to parents and children interacting together, was a GSR sensor activity (adapted from the activities Chapter 8), where parents and children playfully asked each other to tell lies, with the goal of understanding how the data reading of the GSR changed based on the emotional arousal of the person telling a lie.

Moreover, adding a long bench with 5 laptops to the Magic Cubes exhibition, enabled people who wanted to learn more, to stay longer and experiment more with coding. A variety of coding instruction sheets were provided, ranging from simple activities that could engage children as young as 7 who had never coded before, to more complex ones for visitors with more experience. I found that the more complex activities were especially suitable for parents working together with children; for example, in one instance a father who was a software developer, experimented with the code together with his son, with the pair starting from the simple worksheets that were provided and then going beyond them to create their own code that randomized pixels on the Magic

Cubes' LED matrix. It was found that, with these adaptations, at the Science Museum a number of individuals stayed for upwards of 10 minutes interacting with the Magic Cubes, which did not happen at sessions where these adaptations were not implemented. Hence, it was found just how important it is to anticipate how diverse the visitors to an event are likely to be, and provide a variety of adaptations of the activities for different types of visitors – either by preparing them in advance or adapting them on the fly.

A recurring challenge that again was observed in this session, with having a diversity of activities, however, was facilitating them, especially when sometimes 10+ people were visiting the stand at one time. With the increased number of activities, each visitor wanted to find out which was most appropriate to start with, or which was the most exciting. Moreover, adding a diversity of coding activities to the session meant that there were many more questions from the visitors about how the code worked, how to fix errors, and how to upload the programs to the cubes – which did not arise in drop-in sessions where only the discovery-based activities were available. This sometimes also meant that visitors were left having to wait to get my attention or that of another facilitator, especially when I was busy assisting others on a range of tasks. However, many were patient and understanding. Hence, there is a trade-off between providing a limited number of tasks and more variety, varying in complexity. Adding more choice can trigger more curiosity meaning visitors wanting to stay longer and explore them all. However, this means they spend longer interacting with them, making others have to wait. Having fewer tasks to complete, may increase the footfall, but reduce what they an experience and learn. Next, I discuss the tensions arising from the timing and facilitation of drop-in sessions in more detail.

(iii) Tensions of facilitation and time constraints with multiple visitors

In many of the drop-in events, the appeal of the Magic Cubes led to a constant stream of visitors. This sometimes became overwhelming for me, especially at events where I was the sole facilitator. For example, often halfway through my introductory explanation of the Magic Cubes to a group of visitors, other visitors came up to join – requiring me to widen the focus in order to give all a background about what the cubes were, how they worked, and how the visitors could interact with them.

Another challenge that emerged was to ensure that all visitors had a chance to interact with the Magic Cubes, hands-on. While for the discovery-based tasks, visitors tended to readily relinquish control of the cubes to others when they realized others were waiting, this was not always the case for the programming tasks. For example, at the Science Museum, where a bench with 5 laptops was set up, there were a number of instances over the period of the two days, when a queue formed with people waiting to try coding the cubes. Generally, visitors were patient and often, when waiting, left to see the other stands being exhibited in parallel to the Magic Cubes, and then came back when it was less busy at our stand. However, sometimes the need to wait led to frustration. For instance, at one point a grandmother and her grandson became frustrated because they had been waiting for about 10 minutes to try the programming out, having left and then come back, and there still was no laptop available for them to use. The grandmother firmly suggested that I enforce a time limit for how long people were able to stay, in order to keep the line moving and make sure everyone got a chance to try coding the cubes. However, our intention was to be open-ended, letting anyone interested in the cubes, have the time to explore them extensively. This again highlighted the tension in informal environments, of how to ensure that *all* visitors get as much as they can out of the experience. It raises the question of whether it is better to let people regulate their own time, or to enforce time limits to ensure everyone gets a go?

(iv) Fostering audiences' wider interest in physical computing

In organizing the drop-in sessions, our goal was foremost to introduce the Magic Cubes, and provide an engaging experience that left visitors curious about learning more about computing. Indeed, the events led many of the visitors to express curiosity about ways in which they could experiment with programming or technology at home or in school. For example, at every event, we were frequently asked if the cubes were commercially available for purchase, both for classrooms and for homes. Teachers – even those not teaching computing themselves – would ask how the physical computing and IoT content designed for the Magic Cubes, could fit into their school's curriculum for different age groups. Moreover, parents would also ask us what activities or kits we would suggest for their kids to start learning, as well as for their kids and the parents to learn about coding together.

Over time, we began preparing for these questions, by offering resources for people interested in learning more about computing – for example, by suggesting the BBC micro:bit [Micro:bit, n.d.] and other kits that they could purchase that would be easy to get started with, as well as games created to teach young kids about computational thinking. In this way, the outreach sessions were able to introduce new audiences to physical computing in general – beyond just introducing them to the Magic Cubes – and provide people with resources that they could engage with more at home.

10.4.2 Reflections from longer extracurricular events for children and teenagers

The second category of events that were run as part of this research was longer extracurricular events for children and teenagers. Key differences between these types of events and the classroom studies that we ran, were that in contrast to the classroom studies, no teacher was present at these sessions to enforce class rules. Moreover, for many of the events, children did not know each other prior to participating. Below I describe my observations of how well these sessions worked in terms of *(i) the effectiveness of transitioning from discovery to coding*, *(ii) the importance of step-by-step instructor support when starting coding*, and *(iii) the importance of adequate facilitation.*

(i) The effectiveness of transitioning from discovery to coding

Using discovery-based tasks to introduce the Magic Cubes, and subsequently to introduce how to program them, by starting with easy tasks and following on with harder ones was observed to be a productive structure for the context, especially for children who had never programmed before. In particular, EM commented on how seeing what the cubes can do, then manipulating the code to change the physical-digital effects was at the right level of challenge, saying, *"it was challenging enough for them to continue to the next steps but not so steep which sometimes is the case with computing and computing classes – it's so steep that you just think I just can't do it. Where this tangible computing approach makes it much easier and […] more approachable and relevant for them"*

As might be expected, there were always a number of children who were hesitant about coding at the start, saying that they felt intimidated by programming. However, I observed that once they begun coding with the Magic Cubes, many stayed engaged for extended periods of time. Moreover, at the end of the sessions many commented how they had changed their mind about not liking computing. The observation that interacting with the cubes for a brief period of time together with engaging in a small amount of coding was able to change many children's preconceptions and fears about coding is truly remarkable. EM also emphasized this achievement, by saying, *"I think what was interesting was also the fact that we had these kids – also for primary but I'm talking about secondary school now – coming in, never having done anything like this before, and within half an hour, getting to grips with it, understanding how to do it, understanding how to program and how to upload the files […] and really, really focusing for a long time, right, so […] to be programming for 2 hours when you don't think you're good at something, and you're not really into it, and you don't even want to go to the session, I think is a big, big turnaround".*

(ii) The importance of step-by-step instructor support when starting coding

Although the feedback from this category of events was consistently positive overall, one aspect that was sometimes found to be problematic was the transition from the discovery-based tasks to the coding exercises. Specifically, the part that was found to be challenging for some of the children was the first step of understanding how different coding constructs related to the effects on the physical Magic Cubes, as well as how to upload their code to the cube. Although in the classroom study described in Chapter 9, there were no issues observed with transitioning the students from discovery to coding with the Magic Cubes, it is noteworthy that a lot of one on one support was provided to the students to help them achieve this. In the informal setting, a verbal explanation was provided at the beginning of the coding stage, but this may have been too much for the children to take in all at once, who had not had much programming experience with physical computing previously. EM suggested that they would have benefitted from more support and step by step verbal instructions at this stage – like that provided in the classroom. Specifically, she said, "*the only thing that I think could be improved is the initial steps of getting the pupils to that stage before they start uploading the code. […] The only thing that a couple of pupils have said on improvement is having a bit more time with the code, and understanding the code before they upload it. Because once they upload it and see what it does, they start figuring out how it works and how to change things."* It therefore seems that one way this could have been made less challenging, is by having more step-by-step verbal explanation about getting started with coding.

(iii) The role of the facilitator

Overall, I found that these events, even with helpers present, were more difficult for me to run than sessions with the Magic Cubes in classrooms. On reflection, this was largely due to the fact that without a classroom teacher – who had established strategies to keep children calm and focused, and ensure the smooth running of the class – the children would sometimes get overexcited, making it difficult to make sure everyone was paying attention. Moreover, in the classroom studies, the classroom teacher was always able to monitor the students' engagement and understanding, even if not running the studies her/himself, and feed back to me who needed more support. Running sessions without a classroom teacher, therefore, was difficult. With groups of more than 10 children, I found that I needed helpers to smoothly run the sessions. Although I recruited helpers (who were UCL undergraduate or masters students) for each coding event with more than 10 children, I was once unable to find volunteers for a 2-hour event comprising 30 children, who were 12-14 years old. There was a step with uploading the code to the Magic Cubes that I had not explained thoroughly in the instruction sheet, and as such all 30 students were faced with the same error. I was unable to command their attention in a way to get all children focused at once, and therefore had to go to each pair individually in order to help them get through. It was clear that this impeded the flow of the session, with some children having to wait 5-10 minutes for me to come to explain the procedure to them. This again shows just how contingent the success of a session is on the expertise of the facilitator and appropriate in-person guidance.

10.4.3 Reflections from other UCL instructors on public outreach for supporting computing education

This section discusses the findings from the interviews with EM and RH, about their experiences with public outreach – both with the Magic Cubes and with other technologies. They talked about the importance of structuring outreach sessions effectively, and at a general level, how public outreach can play a role with overcoming the barriers that face primary and secondary computing education – for students and teachers alike. In this section, the reflections from the interviews are categorized as follows: *(i) how to best structure coding activities in informal environments?, (ii) the barriers of carrying over learning activities and technologies designed for outreach into teacher-led classrooms,* and *(iii) the importance of highlighting the diversity of development teams to children.*

How to best structure coding activities in informal environments?

One topic that arose during the interviews was how to best structure coding sessions with a physical toolkit in an informal context. RH suggested that an effective strategy is to start with a structured activity where students are given clear instructions which they can all succeed with. This resonated with my own reflections on the best approach to adopt. However, she also stressed the importance of providing them with progressively *less structured* activities that require more resilience and persistence. This is something that could be developed for outreach classes where there are several sessions that a group come to – rather than the type of one-off sessions that are reported here. Specifically, she mentioned how she designed coding sessions for summer schools and coding clubs: *"[…] any activities that we design are exploratory but not totally unstructured. So generally we will start by having that activity where you teach the students something but not everything, and give them something to do that they can definitely succeed at so they can see what the rewards of that activity are. And then you give them something more unstructured to do, where they have to apply what they know, plus learn a bit more, explore and persist – face problems, need to resolve them, maybe need to ask for some help."*

The barriers of carrying over learning activities designed for outreach into teacher-led classrooms

However, RH also discussed that while this kind of emphasis on open-ended exploration may be appropriate for informal settings, it can be much more challenging for teachers leading a class in schools to employ. Specifically, she commented on how as coding acivities become more open-ended, the time associated with supporting individual students increases. This can make it difficult for instructors teaching alone to run these types of open-ended activities. She said, "*so [with the Engduino toolkit] it was important that we provided a lot of assistance in the room. And I think that is one reason why, subsequently, […] we found that it was difficult for teachers to use them in schools, because they just can't access that kind of support.*"

She further elaborated on this by discussing the many variables that arise when teaching computing, especially with new forms of hardware, which are more difficult to deal with as activities become open-ended: *"so a teacher in a classroom will be looking after 30 children, and if there are any technical problems, or difficulty with student comprehension, or just students have questions, and there's only one member of staff -- and there's never going to be more support unless there's some other way of getting into the school in that particular lesson. That precludes teachers from engaging in those sort of open ended teaching activities, certainly in the public sector."*

The importance of highlighting the diversity of development teams to children

Throughout the outreach activities with the Magic Cubes, I noticed that at the sessions where EM was present and introduced me and other members of the team to the children, she would often highlight that the Magic Cubes were designed by a diverse team, especially where women from different cultures and ethnicities played a central role. During the interview, I asked her to explain the reasons for doing this. She answered, "*[the students] couldn't believe it both because they couldn't believe that this was developed by people like themselves, if you like, but also because they were developed by women. And I think that was really important to bust some of the stereotypes behind who does computing, what they look like, what backgrounds they come from, what gender, race, ethnicity they are."* This highlights how the story behind the technology – and not just the technology itself – can be used as a tool to shape children's perceptions of both computer science and computer scientists.

10.5 Discussion

The reflections on the informal sessions described in this chapter, have shown how the Magic Cubes were found to be as appealing to visitors in a range of informal settings – including young children, teenagers and even parents and children interacting together – as they were found to be in classroom settings. This is largely due to their ability to provoke curiosity, excitement and a sense of achievement.

However, a number of difficulties were also observed in adapting the activities for the Magic Cubes to these more informal contexts. The difficulties were not to do with the cubes or the tasks per se, but with how to effectively facilitate visitors' interactions in informal contexts, and how to prepare for more open sessions with unpredictable numbers of visitors with unknown abilities and experience. Hence, there is a hidden cost of adapting the classroom-based tasks to these types of open-ended settings, where there are more unknown variables and less structure and scaffolding in place to manage visitors' interactions and learning experiences. Next, I discuss the reflections in terms of the three research questions posed at the beginning of the chapter:

> ***RQ 10.1:*** *What factors need to be considered when designing learning activities for using the Magic Cubes for a diverse set of visitors in informal settings?*
> ***RQ 10.2:*** *How to determine what kind of experience visitors have in these informal settings, whether they spend a short time with the Magic Cubes or a longer period of time?*
> ***RQ 10.3:*** *What types of facilitation and instructional materials to provide to guide visitors when first encountering the Magic Cubes in informal settings?*

RQ 10.1: What factors need to be considered when designing learning activities for using the Magic Cubes for a diverse set of visitors in informal settings?

Each outreach session carried out throughout this research was unique and some required different types of activities. The key aspects that were important to consider when choosing which activities to bring to a session, and how to present them, were visitors' interest levels, age ranges, as well as the amount of time they had to stay and interact. It was found that one aspect that was also important was how similar or diverse the visitors at a particular session were likely to be, in terms these factors. For example, at some events, the majority of visitors had high interest levels, fell into a similar age groups and had a short time amount of time to spend with the Magic Cubes – which led me to make the decision to bring in more constrained, and immediately interactive activities. In contrast, at other events, the visitors had varying interest levels, age groups and amounts of time – where having a larger diversity of activities, including more open-ended ones they could spend more time with was more appropriate. Hence, being able to anticipate how diverse visitors at a particular event would be, was key to ensuring that the activities chosen to be presented would capture their interest and give all the opportunity to meaningfully interact with the Magic Cubes.

RQ 10.2: How to determine what kind of experience visitors have in these informal settings, whether they spend a short time with the Magic Cubes or a longer period of time?

Answering this requires considering that a positive learning experience would have a different definition in various spaces. For example, in some contexts, namely short, drop-in sessions, it was not possible to convey learning outcomes like how to program sensors and actuators; the envisioned outcome was instead to provide an enjoyable experience and spark visitors' curiosity in physical computing, as well as to provide them with resources to follow this up at home. In others, like the structured coding sessions, the goal was to both spark curiosity in physical computing and IoT, and ease children into programming, by showing them that it can be an enjoyable and exciting activity.

What was also found was that the short, discovery-based tasks were successful in all of the diverse settings, as a way of helping achieve the diverse goals of the sessions. At drop-in events, these served as a way of opening up visitors' conversations as to what they could do at home to learn more. In more structured sessions, the discovery-based tasks were also successful in introducing the children to the Magic Cubes toolkit as a bridge to more complex programming tasks. Therefore, providing an engaging way to quickly get started with experimenting with the Magic Cubes, coupled with allowing more complex activities where appropriate, was found to be a good strategy across informal contexts.

RQ 10.3: What types of facilitation and instructional materials to provide to guide visitors when first encountering the Magic Cubes in informal settings?

It was found that in drop-in sessions where the activities were exploratory and constrained, presenting how to interact with the Magic Cubes verbally was sufficient. The "honeypot effect" [Rogers & Brignull, 2002] for these types of activities also meant that many visitors explained to each other how to get started, decreasing the burden on the facilitator. However, in spaces where a larger diversity of activities was presented, facilitation was more difficult and time-consuming, as it was less clear to the visitors where to start or how to interact. Simultaneously, text-heavy instructions were off-putting, especially to children. This suggests that when a range of activities is presented in an informal environment, labeling that is well-designed, clear and brief is paramount to reducing the burden on the facilitator, while also enabling visitors to direct their own interactions. The finding that designating separate spaces, for example for coding versus exploring, also contributed to successfully guiding visitors and providing a narrative for how the Magic Cubes work, is also reflective of previous design principles proposed for learning in informal environments (e.g., [Hall & Bannon, 2006; Lyons et al., 2015]).

In contrast, in sessions where 10-30 children were completing activities together it was found important to provide the same activity to all and provide more step-by-step support to the group, rather than to the individual – especially at the beginning. While providing coding activities that are open ended and creative is often considered more engaging to children, it is important that the learners have enough knowledge of the coding constructs to self-direct the majority their learning, otherwise facilitation can become too difficult to manage, especially for one or two people. As was suggested in the interviews with the public outreach experts, this is an issue not only in informal environments, but also in schools – where a class teacher is often the sole facilitator. A challenge that remains unresolved here, however, is whether open ended and creative coding can be successfully done in short sessions, for example those that are only 30 minutes to 1 hour long.

Finally, beyond these research questions, what bringing the Magic Cubes to outreach events revealed, is how the impact of a technology for learning about computing can be extended beyond the classroom. While the events enabled us to reach a wider audience – as expected – they also were able to get teachers and parents interested in new ways of fostering children's curiosity about computing at home and in schools. Moreover, it was found that even the act of showcasing the diversity of the research team, was impactful in challenging children's preconceptions of both computer scientists and computer science.

10.6 Summary

This chapter has shown the many benefits of bringing novel physical computing technologies like the Magic Cubes to a variety of informal learning contexts. It has also revealed how best to design activities for the different settings and how to present them, by taking into account the varying needs of the visitors. For example, not all outreach needs to focus on fostering specific learning outcomes – sometimes, it is enough to spark curiosity in the toolkit and what it can be used for, by making a task engaging and playful. Further, what was revealed was that discovery-based activities in particular, especially when made to be easily interactive, can be a great introductory tool to a technology, whether presented as a stand-alone exhibition, or in conjunction with more complex learning activities. In sum, there is much value in designing physical computing toolkits with both classrooms and informal contexts in mind.

CHAPTER 11: DISCUSSION

The aim of this research has been to investigate new approaches to teaching digital fluency within the scope of IoT. Specifically, this thesis has addressed three overarching research questions:

1. *What IoT topics are appropriate to teach to children?*
2. *Can IoT topics be taught through discovery learning? If so, how?*
3. *How can learning about IoT be made more inclusive?*

First, by reviewing the benefits of a variety of existing approaches to teaching computing, current best practices for teaching computing were identified. The review revealed that while there has been much work on teaching computational thinking and coding in the literature, there also appears to be much promise for teaching abstract computing topics through discovery-based learning - especially if learning is designed to capitalize on embodied interaction and collaboration. It also revealed a gap in the literature concerning teaching children about new technology paradigms, including IoT, as well as teaching critical thinking about technology. Through an interview study with IoT experts, the research then proposed IoT topics suitable for children who are just starting to learn about computing. What was highlighted was the importance of considering the *utility* of teaching IoT topics when choosing which to teach, as well as making a distinction between teaching for conceptual understanding and for higher-level thinking. The findings also called attention to the central importance of introducing children to thinking critically about technology in general – especially as emerging technology paradigms are constantly in flux, with increasing implications on data privacy and security.

Next, a design-centered approach together with in the wild evaluation studies, explored how best to teach children a subset of the IoT topics derived. Specifically, the focus was on teaching about the functionality of IoT hardware, like sensors, actuators and network connectivity, and on enabling children to critically reflect about data and the act of sensing. The empirical approach used was to investigate how these topics could be introduced through discovery-based learning activities with a custom-made tangible interface, called the Magic Cubes. Three in the wild classroom studies, and observations from a variety of informal learning contexts demonstrated how using the Magic Cubes through a discovery learning paradigm engendered much playfulness, collaboration and curiosity, for children of all ages and abilities. Furthermore, the research showed how not all discovery learning is equally effective. For example, highly open-ended, exploratory activities with appropriate guidance that was provided in situ, were found to support the most reflection about abstract concepts. In contrast, making discovery tasks goal-based, or not providing enough guidance, limited the extent to which children abstracted away from the hands-on activity to reflect on what they were learning. The findings thus highlighted the central importance of interaction design and pedagogical theory, for: developing learning approaches that support collaborative learning for a diversity of children; capitalizing on children's existing knowledge to promote reflection; and offering appropriate scaffolding to help children switch between an immersive, hands-on activity and reflecting on what they are learning.

This chapter discusses the contributions of the research in terms of the three overarching research questions posed, by reflecting on the key findings from each of the chapters presented in this thesis. By doing so, it highlights new directions for digital fluency education, especially in terms of the types of learning outcomes that should be considered when teaching children about IoT and other novel technology paradigms. Moreover, it contributes new understandings about how discovery learning with tangible interfaces can be designed to be simultaneously playful, collaborative and inclusive, while enabling children to reflect and think critically about abstract concepts. The chapter also discusses the methodology employed throughout this research, the limitations of the research undertaken, and finally proposes directions for future work.

11.1 Which IoT Topics are Appropriate to Teach to Children?

The interview study presented in Chapter 5 addressed the identified gap in the literature concerning which IoT topics can be considered relevant and appropriate for children to learn about. The findings suggested that what is key is considering what topics provide a "useful skillset" to children. A "useful skillset" is conceptualized here as one that teaches children enough to understand broadly how IoT works, and reason about the limitations of IoT, while also being able to think critically about the usefulness and societal or ethical implications an IoT system might have. The key goals of providing such a skillset are enabling children to make sense of how IoT relates to their lives, and importantly, piquing their curiosity in further learning about IoT and other technologies. Through this framing, other, more technical IoT topics were considered to be too complex or potentially off-putting for these goals. For example, learning in detail about concrete implementations of IoT devices – such as how the circuits of IoT devices are designed, or the differences between different wireless networking protocols – was considered out of scope for the criterion of "usefulness".

What the research also highlighted, is the distinction between teaching for *conceptual understanding* and teaching for *higher level thinking*, when teaching about IoT. In practice, this means that it is key to promote both declarative knowledge (such as understanding how a piece of hardware works) and thinking practices that enable children to analyze and evaluate the value of a device or IoT system. From the suggestions of the participants interviewed, a framing of potential IoT topics was derived, which was used as a basis for the learning activities that were designed in the later stages of research. This framing included both "conceptual understanding outcomes" and "higher-level thinking outcomes", and is reproduced from Chapter 5, in Table 11.1 below.

Table 11.1: A table of the IoT topics identified as being potentially suitable for children, as reproduced from Chapter 5.

Topic	Conceptual Understanding Outcomes	Higher-level Thinking Outcomes
Hardware	What are microcontrollers, sensors and actuators? How do they work? Are they accurate/reliable? How do they work together to create an IoT device?	What are the limitations of IoT hardware? What happens if a piece of hardware is inaccurate or unreliable?
Data	What is data? How can data be represented? How is data physically stored?	Are some types of data representations better or more informative than others? What is the value in storing this data? Does this vary depending on the context?
Systems	How do individual IoT devices connect to others/to a larger system? How is data transferred within an IoT system?	What is the relationship between the individual device and the system of which it is a part? What is the value in this device working as part of a bigger system?
Privacy	What is privacy? What are the principles of designing privacy into an IoT system?	To what extent does privacy matter for this IoT system? What do different data representations (e.g., real time, aggregated) mean for the privacy of this system?

By placing an emphasis on conceptual understanding and higher-level thinking, this framing can be seen as divergent from more traditional approaches to teaching computing. For example, the English national computing curriculum for primary school children is primarily concerned with promoting a more procedural understanding of computing and computational thinking [UK Department of

Education, 2016]. This includes for example, teaching children about how algorithms work, how to code in different programming languages, and how to use technology safely and respectfully. Much empirical work on teaching computing to date has also been concerned with activities that promote computational thinking, and that enable children to engage with *making* and *creating* with technology. These approaches, of course, are crucial to enabling the next generation to "construct things of significance" with technology, which has been described by Resnick as being fundamental to digital fluency [Resnick, 2002]. However, they do not usually explicitly promote reflection about the technology itself – which is, in part, what this thesis aimed to address.

What the analysis of the interviews highlighted, therefore, is that there needs to be a different focus in modern digital fluency that *complements* the dominant paradigm of teaching children to "construct" things and ideas with technology, but that also explicitly engages children in moving between understanding how a technology works, and thinking critically about its limitations and implications. This expanded notion of digital fluency is seen as applying to learning about IoT, but equally to other technologies. Based on this perspective, next, I propose a new framework for modern digital fluency.

11.1.1 Towards a new framework of digital fluency

Sharp, Rogers and Preece [2019] define a framework within Human-Computer Interaction as a "set of interrelated concepts and/or a set of specific questions that are intended to inform a particular domain area." Based on the research presented in this thesis, I propose a framework that distinguishes three types of knowledge that I suggest are fundamental to modern digital fluency. These are: 1) *declarative understanding* of how a technology works; 2) the ability to *think critically* about the implications of a technology; and 3) the ability to *create use cases and applications* for a technology. This framework also suggests the types of learning approaches that might be suitable for each type of knowledge – based on the literature reviewed, and the research presented in this thesis. The framework is presented in Table 11.2.

Table 11.2: A framework of the three types of knowledge embedded in digital fluency.

Type of knowledge	Example in the context of IoT	Potential approaches to learning
Declarative understanding of how a technology works	Learning how a sensor gathers data, and how data is transferred between connected devices	Exploring and experimenting with existing technologies (e.g., through discovery learning); structured making
The ability to ***think critically*** about the implications of a technology	Analysing, evaluating and reflecting on the reliability and accuracy of a sensor in different contexts	Learning through discovery; discussing the limitations of existing technologies
The ability to ***create use cases and applications*** for a technology	Using a toolkit to build and program an IoT device or system	Coding, designing, making

Whereas most of the widely adopted teaching approaches focus on teaching for *declarative understanding* and/or for the ability to *create use cases and applications* for technologies, the novelty of this proposed framework is the addition of *critical thinking* as an explicit outcome of digital fluency. Hence, its purpose is to provide other researchers with a way of considering what aspects of digital fluency their approach aims to teach, and what they are leaving out. The framework can also be used not just for teaching IoT, but also other aspects of computing, like machine learning, artificial intelligence, or robotics.

The different types of knowledge embodied in this framework are not viewed as being linear. Thus, the framework does not aim to impose a specific progression from one type of knowledge to another. For example, a learning approach might start from teaching a declarative understanding of a particular topic and then move to enabling critical thinking, or start by getting children to learn how to create digital artefacts and then to critically reflect on the implications of these. Based on the IoT topics derived in chapter 5, which highlighted the importance of both *conceptual understanding* and *higher-level thinking* to IoT education for children, the thesis addressed how the first two categories of knowledge in the framework – that is declarative understanding and critical thinking – might be taught. The empirical focus was on investigating the potential of discovery learning to teaching these. The next section discusses in detail the value and limitations of the discovery learning approach for these types of knowledge.

11.2 Can IoT Topics be Taught Through Discovery-based Learning? If So, How?

The research in this thesis started with the hypothesis that hands-on, discovery learning might be a suitable approach to bringing complex IoT concepts to a level that children just starting to learn about computing can understand, especially those who are 8-12 years old. While discovery learning has been demonstrated to be a valuable pedagogical method in a variety of domains, within the domain of computing education, the emphasis has been more on learning through making and coding. Therefore, while some of the sessions designed in this research also included elements of making and coding (especially those in Chapters 9 and 10), the empirical focus was placed on understanding how and to what extent discovery learning can get children started with learning about IoT.

What the findings throughout the research have demonstrated, is that playful discovery learning tasks can promote much curiosity about IoT and physical computing, while sustaining engagement and promoting collaboration, for learners of all ages. This was observed across a variety of contexts – from mainstream and SEN classroom settings to informal learning settings like museums and coding clubs. The mysterious sensor-actuator effects that were designed for the Magic Cubes were found to captivate all the groups of children observed, and engendered forms of physical play like jumping, dancing and finding new ways to explore hidden data in the environment. In turn, the physical way in which the children interacted with the Magic Cubes also enabled them to observe each other and often playfully compete with each other, to uncover the hidden effects embedded in the tasks.

The hands-on experience afforded by the discovery learning approach was found to provide children with a foundation for discussing the implications of data sensing and IoT more broadly. It also provided them with a basis from which to move on to more expressive forms of learning, like coding. Moreover, in informal contexts, the discovery learning activities designed for the Magic Cubes were also found to be successful in getting children, parents and teachers alike, interested in what other resources exist for learning more about IoT and physical computing. Together, these findings demonstrate how discovery learning can be used as an introductory tool for abstract computing topics, and as a way to trigger further interest in learning more about IoT.

Another research challenge addressed was how to design discovery learning activities that were not just playful and engaging, but also that would enable children to abstract away from the immersive hands-on activity, and reflect on the IoT concepts that the tasks aimed to convey. It was found that this was contingent on how the discovery tasks were designed, as well as the types of guidance provided to the children, both in terms of the learning materials and verbal instructions provided. Next, I discuss in detail what factors made discovery learning with the Magic Cubes successful, drawing on the key findings from the empirical studies presented in the thesis.

11.2.1 What types of discovery tasks are effective?

The discovery-based learning tasks presented throughout this thesis were designed iteratively, and adapted by taking into account feedback from HCI experts, and the findings from deployments in classrooms and in informal learning contexts. This iterative process revealed that not all discovery learning with the Magic Cubes was equally effective at promoting reflection, collaboration and engagement.

The importance of limiting variables and designing for open-ended exploration

One factor that was found to be important at the beginning of this research, was to limit the variables to be discovered when just getting started with learning. For example, as demonstrated in Chapter 6, starting out with a system of interconnected Magic Cubes, rather than one cube at a time, made it difficult for users to understand what the system as a whole was doing. This is because as without a prior knowledge of the range of actions that elicited digital effects on one cube, figuring out what effect one cube might have on another was not intuitive. In contrast, when discovery tasks comprising systems of interconnected cubes were presented after learners had developed an understanding of one cube's functionality, as tested in Chapter 9, the system effects were found to be easier for them to discover. This demonstrates the importance of scaffolding discovery learning tasks, so as to introduce a limited number of new variables at a time.

Another finding was that goal-based, competitive games were less successful than open-ended, exploratory activities in eliciting reflection about the concepts instantiated in the tasks. Specifically, when users interacted with a goal-based game (Chapter 6), their focus was on getting a high score or doing better than their partner. In turn, open-ended, exploratory activities enabled more discussion to take place about the functionality of the cubes, and about the abstract concepts embedded in the tasks.

Capitalizing on embodied interaction to promote understanding and reflection

As demonstrated in the study in Chapter 8, capitalizing on children's knowledge of their own bodies proved to be a powerful mechanism for promoting reflection and triggering critical thinking about IoT concepts. For example, when they were able to explore data about their own bodies (e.g., GSR, pulse and step count), rather than about the environment (e.g., light and temperature), they reasoned more extensively about whether and why the sensors that they were using were accurate or reliable. This is because they were able to more directly tie the data readings displayed on the LED, to a "ground truth" of how many steps they had taken, how stressed they felt, or how quickly their heart was beating. Using physical, embodied actions – for example, exaggerated reaching towards and away from light sources – was also found to help children "debug" their understanding of the code they had written in programming tasks (Chapter 9). These findings corroborate with Papert's theory of how "body-syntonic" reasoning can support learning of abstract concepts, which Papert instantiated in Logo, by enabling children to relate programming constructs to the movement of their own bodies [Papert, 1980]. Here, it was shown how designing discovery learning activities that involve the body and embodied interaction, can also be powerful for promoting understanding of abstract concepts.

Capitalizing on embodied interaction was also found to facilitate collaborative learning, both within pairs and small groups, and throughout a classroom of children more broadly. This was a finding that was observed in all three classroom studies (Chapters 7, 8 and 9). The noticeable and attention-grabbing physical actions that were paired with visible digital effects, triggered much sharing, showing and observing of others in the classroom. In turn, children monitored other groups who were completing the same tasks, and worked out who might be able to provide them with help or support.

From this perspective, it can be seen that the various forms of embodied interaction that took place in the classroom drew the children's attention to each other and in doing so helped them to progress with their own learning. This is a key benefit of tangible interfaces, that has been frequently cited in the literature, stemming back to Suzuki and Kato's work on tangible interfaces for computing education in the 1990s [Suzuki & Kato, 1995]. However, as well providing a physical point in space to direct joint attention to, the handheld form factor of the cubes also engendered explicit turn taking to take place during discovery learning, by enabling children to grab and hand over the cubes. This was found to support children in implicitly negotiating strategies for discovering together.

In sum, what the findings throughout this thesis demonstrate, is that embodied interaction with a tangible interface can take many forms. There are various ways in which the body can be capitalized on to support learning with a tangible interface – in this research, the ones that the Magic Cubes supported were: (i) engendering performative and physical actions that enabled children around a classroom to monitor each other's progress; (ii) enabling gestures that supported children in negotiating turn taking during the learning process; and (iii) enabling children to draw on the knowledge of their own bodies, in order to reflect on abstract concepts.

Another crucial factor for promoting successful discovery and reflection about the hands-on tasks, was found to be appropriate guidance. Specifically, the tasks that were most successful in enabling "stepping out" from the activity to reflect on what the cubes were doing, were ones where the learner was provided with *in situ* guidance and feedback, which was tailored to their own learning trajectory. Next, I discuss the role of guidance for successful discovery learning in more detail.

11.2.2 What is the right level of guidance when learning IoT through discovery?

Although discovery learning has much promise as a pedagogical approach, as discussed in the literature review, there is evidence of the failure of "pure discovery learning," where learners receive little to no guidance during the process of discovery [Mayer, 2004]. Hence, a deliberate choice was made in this thesis to design discovery-based activities that were supported by varying levels of guidance. By guidance is meant, providing instructions and cognitive scaffolding to help the learner complete the task, which can be either verbal or written. The provision of various levels of guidance was found to be valuable throughout the classroom studies. Many times during the discovery process, students 'got stuck' or ran out of ideas for what to explore next. At these junctures they asked the researcher, the teacher or looked at the provided written instructions. Hence, while the presence of guidance in a discovery task may seem contradictory, its value – provided it is in the right form – is to enable learners to stay on the right track during a discovery activity by helping them to reflect on what they are doing and providing them with corrective feedback when they misinterpret or miss a step in an activity.

The effects of too much or too little guidance

It was found that different types of guidance varied in how well they helped the students. Some were more successful than others, especially for keeping children engaged with the activity and encouraging reflection about what the physical-digital mappings embedded in the Magic Cubes represented. Specifically, it was found during the initial design workshop presented in Chapter 6 that longer, step-by-step written instructions that provided hints about how to complete an activity, were considered off-putting and disengaging. This was especially true when the learner was given an exciting, novel artifact and did not want to spend time reading a set of instructions before getting started with exploring how it worked.

Conversely, adopting a strategy with a lower level of guidance was also not completely successful, in terms of encouraging higher level thinking about IoT. In Chapter 7, where instructions were only provided verbally at the beginning of the activity and periodically during the activity, many children were able to discover how physical-digital mappings embedded in the cube worked from their own explorations. However, there was little evidence of abstraction from the learning activity taking place when adopting this approach. This can be explained partially because the type of feedback that was provided to them in situ was limited. Specifically, in this first classroom study, I did not have the experience to ask the instructors to discuss with each of the groups at a deeper level, what the mappings and data readings meant in the context of IoT. Thus, they focused more on making sure that the students understood what the task was asking them to do, and helping them to locate the various hardware components on the cube.

Together, the implication of these observations from the initial design workshop and the first classroom study, is that children need guidance and prompting to engage in higher-level reflection, that goes beyond just understanding how digital-physical effects embedded in a discovery activity work; this is especially important to enable them to make sense of what they are doing and to think more abstractly about the concepts underlying the activities they engage in. Simultaneously, the findings suggest that it is better to provide feedback as the task progresses rather than as a step-by-step set of instructions at the beginning of the task.

The effectiveness of tailored, in situ guidance

The principle of providing more in-depth guidance in situ was subsequently adopted in the study presented in Chapter 8, with much success. Specifically, it was found that providing learners with field journals that they could reference when they were stuck or when they wanted to explore what else the Magic Cubes could do, helped them to work at their own pace and also initiate new ideas and hypotheses. Moreover, by providing more in-depth verbal support from instructors – by way of asking the children guiding questions, such as prompting them to relate the data collected by the cubes to their knowledge of their own bodies – it was possible to trigger more reflection among the students about the implications of their observations. This was found to be a key mechanism for supporting critical thinking processes such as analyzing the accuracy of sensor data and inferring the contexts in which it might be inaccurate, uninformative or unreliable. Finally, the guided group discussion that was held at the end of the session prompted them to abstract from the hands-on activities, and consider how what they had learned related to IoT more broadly.

In some ways, the findings that a more extensive and situated form of guidance was needed to engage children in critical thinking processes is to be expected; especially younger age groups are unlikely to engage in this type of higher level thinking spontaneously when completing an immersive hands-on activity. The findings showed how and in what instances providing guidance enabled the younger children to "step out" to reflect on what they were doing [Ackermann, 2001]. In this research, providing written guidance that they could use when needed, together with individualized, verbal guidance that went beyond hinting what to do next in a task, was key.

What these findings highlight, is that the type and level of guidance is just as important as the physical design of the interface itself, when the goal is to support children in reflecting on the task, and engaging in higher level thinking processes. Although this is an idea core in the learning sciences (e.g., [Rosenshine, 2009]), much design research in HCI on developing new toolkits for learning still focuses primarily on the design of the interface and considering how the interface will engender certain types of interaction. In turn, the level and form of guidance that is provided in situ – especially by instructors or supporting materials – is often underspecified. Other recent work in the domain of learning games has also highlighted the importance of guidance to helping children progress and reflect on their learning [Benton, Vasalou, Barendregt, Bunting, & Revesz, 2019]. The implication from this thesis is that it is important to be clear about the type and level of guidance that will be provided to learners during a discovery task.

However, there are practical concerns for using this method for the average classroom of 20-30 children – especially when there are typically only one or two adults present. The next section discusses how to overcome this dilemma in more detail.

The question of guidance when handing sessions over to the teacher

A dilemma I wrestled with throughout the PhD was how easily the learning activities reported in the thesis could be "handed over" to teachers to run, when multiple researchers are not present to facilitate. Even though initially, a goal was to work out how best to package the learning activities for a teacher to run for themselves, it became clear from each study that this would not be feasible. One of the reasons it was decided not to follow through with this was that the Magic Cubes and supporting software were not in a robust or reliable enough form to be handed over. Developing the hardware and software infrastructure for others to take control of and adapt for their own use was not part of the remit of this thesis. Instead, the focus of the research became what other factors, beyond the hardware and software itself, would determine if the learning activities could be handed over. A key concern that emerged was classroom management for open-ended discovery learning, which was found to be problematic for large classes.

In the majority of the classrooms that I visited throughout this research, there were between 20 and 30 children in a single class with only one main teacher, occasionally with an additional teaching assistant. However, during the research sessions in these classrooms, usually three or more visitors (including myself) were present and also supported the children throughout the learning process. Hence, it is unclear how well the approach of discovery learning with a high level of in situ guidance would carry over to these types of classrooms, when the researchers and helpers are not present. It became clear after conducting each study and outreach event, that this type of approach is instructor-intensive. Indeed, my own experience of leading an outreach session in an informal environment for 30 children without helpers, demonstrated to me the difficulty of running some of the learning activities alone (see Chapter 10). When there is just one teacher or researcher managing a class, it is far more challenging to address every child's questions in a timely manner, and to monitor how far along each child is in the activities.

Since it will not always be possible to have a researcher or group of helpers at hand a question this raises is: are there other strategies that could be developed to maintain student interest, help them when they get stuck and also to progress with their understanding of what they are doing and learning? What compromises might need to be made to the type of guidance provided, without multiple instructors present in the classroom? What methods could be deployed to prevent children from becoming frustrated or bored?

The research findings reported here showed how, with the support of appropriate learning materials, many children were able to proceed through the tasks at their own pace, referring to the instructions when they were stuck – suggesting that strategies could be adopted to support them in learning independently to a greater extent. One strategy is to provide more step-by-step, contextually-based guidance, similar to the field journals, presented on printed cards or a screen, that children could refer to by themselves when needed. However, it seems that it would be key for the guidance to ask questions that prompt reflection, and for a teacher to ensure that the children engaged with these. Furthermore, could the use of peer to peer learning be capitalized on more, where children prompt each other to reflect on the task, rather than relying on the teacher? Teachers could also use different instructional strategies to provide guidance to students, for example, by having more frequent group discussions, or presenting the instructions along with probing questions in a more structured way to the class as a whole.

In conclusion, it may be easier to hand over the discovery learning approach adopted here to teachers who have smaller classrooms, or those which have a high teacher-student ratio. For instance, SEN classrooms like the one in which the study presented in Chapter 9 took place, are ideal for a discovery learning approach with a high level of instructor-led guidance, as these classrooms often have a higher ratio of teachers to students, and prioritize individualized student support. For larger classes, it may be the case that helpers will still be needed when following the discovery learning approach, although there may be other strategies, as suggested, that teachers can adopt to help them.

11.3 How Can Learning About IoT be Made More Inclusive?

The third research question addressed in this thesis was concerned with *how can learning about IoT be made inclusive?* The research reported here was concerned with how to make learning about IoT through the use of the Magic Cubes inclusive to SEN students, who had a range of abilities and learning challenges.

11.3.1 Including SEN students in IoT learning

As the research presented in Chapter 9 demonstrated, the Magic Cubes were found to have the same benefits in a SEN classroom, as in mainstream classrooms, in terms of fostering engagement, curiosity and collaboration. However, it was found that a number of pedagogical strategies needed to be put into place in order to make the learning activities a success. Similar to the discussion above, the strategies were predominantly to do with how tasks and instructions were presented, as well as the level of support provided in the classroom. As the findings in Chapter 9 suggest, a good approach was to:

1. *Make sessions and learning activities self-contained so students do not feel left out.* It is often the case that a SEN student has to miss a session or part of a session, due to conflicting appointments or activities organized by the school. These absences are much more frequent than in a typical mainstream classroom. Moreover, some SEN students have difficulties staying focused on one learning activity for an extended period of time and sometimes need to take time out and be able to come back where they left off, without feeling left out.

2. *Make tasks short rather than filling up the full class time*. This enables students who find it difficult to focus for a longer period of time, to self-regulate their attention.
3. *Provide instructions in a variety of representations*. Providing instructions verbally, visually and in a written format enables students with different abilities to engage with the learning activities – including those who have difficulties with reading, or with remembering extensive verbal instructions.

What was striking about using these strategies was that putting them into practice required only relatively small adjustments to the activities that were designed for mainstream classrooms. However, it is unclear how some of the strategies might scale up for longer interventions for learning computing. Specifically, ensuring that tasks are self-contained and short can be at odds with a curriculum where concepts of increasing difficulty build directly on each other, or where children are asked to work on a single project over a longer period of time.

Another method that was found to foster inclusivity, especially for students who had difficulty sustaining joint attention with their peers, was to make some tasks wholly physical and tangible – in this research, this was done through the making and discovery-based activities. These types of tasks were found to enable the students with Autism Spectrum Disorder (ASD) to collaborate and focus more. In turn, the finding that just adding an element of programming on a computer led to decreased collaboration for some of the students with ASD suggests that it can be better to enable the students to focus on the physical device when learning about computing with peers. Indeed, previous research on how tangible interfaces can enhance collaboration for learners with autism has corroborated this idea [Farr, Yuill, & Raffle, 2010]. Other physical kits that have come to the market, such as LittleBits [Bdeir, 2009] or Topobo [Farr, Yuill, & Raffle, 2010; Raffle, Parkes, & Ishii, 2004] that do not include computer screens may be well suited to this purpose. However, what is also evident that it is not enough for the interface to be tangible to enable increased collaboration; instead, the level of collaboration is contingent on the level of control that the interface gives to each collaborating partner, which can configure how joint awareness arises [Yuill & Rogers, 2012]. In the case of the Magic Cubes, the effect of increased joint awareness for learners with ASD in the purely "physical" tasks was likely due to the fact that these made it easier for both partners to contribute dynamically – by moving between interacting together and taking individual turns with the cubes – as opposed to tasks in front of a computer, where participation was configured by who had access to the keyboard and mouse.

The research reported in Chapter 9 did not address teaching the students to think critically about the concepts of reliability, accuracy and how informative sensed data is. This was because it was decided to focus on topics that mapped directly to the students' current GCSE curriculum, and as such the sessions placed a heavier focus on learning about hardware, computational thinking and coding. A question that remains to be addressed, therefore is whether critical thinking could be taught in the same way to SEN students, as those in a mainstream classroom?

The focus of the research reported here was mainly on students with mild to moderate cognitive disabilities, and does not account, for example, for the needs of students with physical disabilities. The current design of the Magic Cubes is likely to exclude individuals with some physical disabilities, for example, due to the cubes' small components, which require precise and stable hand movements to connect together. As the actuated effects of the cubes are currently purely visual, this also excludes many individuals with visual impairments. Other work has begun to address these gaps in design, notably Microsoft's recently commercialized Code Jumper toolkit, which comprises easily connectable tangible beads that output music to provide an alternative, inclusive experience for children learning to code [Morrison et al., 2018]. In sum, there is still much to be done in the realm of inclusive design to continue building knowledge about how future toolkits can be made inclusive to more diverse audiences.

11.3.2 Other forms of inclusivity

Throughout this research, an implicit goal was to foster gender inclusivity when teaching children about computing. The choice was made to do this by striving for a gender balance throughout the research. This was accomplished for the most part, with the exception of the study which took place in a SEN classroom (Chapter 9), where there was a higher percentage of boys than girls, and in one session which was run in an all-girls school (Chapter 7). The empirical focus in this thesis was not on assessing gender differences. However, what was striking was that throughout the research, there were no observed gender differences in how the Magic Cubes were used in the different settings, or how immersed students of all genders were in the learning activities.

It is worth noting, too, how one of the core design principles behind the Magic Cubes was gender neutrality [Johnson, Shum, Rogers, & Marquardt, 2016; Rogers et al., 2017]; this was instantiated through design choices like creating a white colored printed circuit board, making the toolkit into an abstract shape not tied to gendered toys, and adding multicolored lights for children to experiment with. A core factor of the learning activities themselves, was that they strived to make learning meaningful by rooting it in a physical context, through which children could experiment with their environment. They were also designed to enable children to devise their own use cases for the cubes based on their own interests (e.g., mapping colorful lights to dance moves or imagining how an IoT cube could be used to monitor their pet). The various ways the children appropriated, used and talked about the Magic Cubes in the studies reported here, supported this design rationale. They provoked interest, curiosity and intrigue in all children (and adults) who encountered them. There was no mention of the cubes being a tool suited for boys or girls. Hence, it was an excellent choice of an IoT computing kit, that was personally meaningful to all children, sparked their imaginations, and enabled them to tie real world scenarios to sensors, data and wireless connectivity.

There is a body of work within HCI focusing explicitly on sparking girls' interests in computing, by designing tools around activities that are often associated with female interests – for example, crafting and sewing (e.g., [Buechley, Eisenberg, Catchen, & Crockett, 2008; Kafai & Peppler, 2014]). These have been met with a level of success, especially in diversifying the perceptions of what computer science can be used for. On the flip side, however, it has been suggested they can also perpetuate assumed gender norms and stereotypes [Holbert, 2016]. What the Magic Cubes demonstrate, is that it is not always necessary to design around gender norms when the goal is to promote more inclusion and equity; instead it is about ensuring that learning is meaningful, fun and enables creativity for all regardless of their gender.

A further goal of the research was to reach a diversity of children; not just those from mostly well-off backgrounds. This was done by working closely with the UCL Engineering Engagement department, which prioritizes engagement with schools and groups from deprived areas of Greater London. By making connections with UCL Engineering Engagement's collaborative partners, I was able to run both the classroom studies and the informal outreach activities in a variety of Greater London boroughs with diverse demographics. Similarly, across the different settings, I observed no differences in the children's interactions with the Magic Cubes, regardless of their background. A difference that I did observe, however, was with the teachers; I found that often, teachers from schools in less well-off areas seemed more excited about the potential of the Magic Cubes in terms of what they could add to their classrooms, than those teachers from privately funded schools. This is perhaps because the former group received fewer external opportunities for their students to engage with emerging technologies than the latter. Another observation based on a comment made by one of the public outreach experts (interviewed in Chapter 10) was how the Magic Cubes sessions enabled children to meet a diverse team of computer scientists and engineers, to whom they could relate, and who could challenge their perceptions of what a computer scientist looks like. This also demonstrated how there can be much value in engaging with a diversity of audiences when bringing a new technology to schools and informal environments, which transcends the value of the technology or lesson itself.

11.4 Reflections on the Methodological Approach

The methodological approach adopted to answer the research questions set up for the thesis was predominantly to video record children interacting with the Magic Cubes, and to use qualitative coding and analysis techniques to understand how children learn with them. This was to make sense of how the children's interactions contributed to the process of understanding the domain concepts instantiated in the tasks. This approach was successful in showing, with a high level of granularity, how collaborative and embodied interaction contributes to the processes of discovery and reflection, especially depending on other materials provided for a task, and the socio-material context of the classroom. It was also successful in demonstrating how collaboration contributes to the development of a shared understanding between peers in a classroom, and the extent to which children remain cognitively engaged during the learning process.

The methodological approach was drawn from previous work on Interaction Analysis [Jordan & Henderson, 1995] and from the field of Computer Supported Collaborative Learning more broadly (e.g., [Stahl, Koschmann, & Suthers, 2006]). However, as Chapter 3 demonstrated, within HCI design research on new interfaces for teaching children about computing, evaluation approaches are often less granular, focusing on quantifying learning outcomes (e.g., [Horn, Crouser, & Bers, 2012; Johnson, Shum, Rogers, & Marquardt, 2016]) or evaluating a product that a child has created at the end of the learning process (e.g., [Brennan & Resnick, 2012]). These types of approaches offer more insight into the extent to which an intervention or new interface, as a whole, influences learning as an *outcome*, but less about *how* those outcomes arise during the learning process. In contrast, the more in-depth, qualitative approach used in this research, was able to demonstrate aspects of the interaction that these other approaches would not. These included demonstrating the influence of task-related materials and instructors on the learning process; elaborating *how* reflection and critical thinking unfold in situ; and shedding light on the extent to which a social context influences a learning experience. The findings revealed just how contingent a child's learning experience and level of reflection are on factors that are not *directly* tied to the design of the interface itself (e.g., how learners are instructed and supported throughout the task), which is not always acknowledged in work proposing new interfaces for learning.

11.4.1 Limitations of the methodology

The approach of video recording and analysis adopted, however, was not without its challenges. In all of the school studies, the data collection was influenced by the constraints of working in a real classroom setting. Because gaining access to the classrooms during the school day was not possible, I was not able to test the recording equipment prior to running the research studies. This meant in practice that data recording could not be rehearsed in a fully realistic setting prior to the studies, and as such, with each adaptation of the data collection protocol, new problems arose in situ, that had to be overcome.

For example, in the first set of classroom studies (presented in Chapter 7), I decided to exclusively use video cameras to record how children interacted. I set up a number of cameras in the classroom, which successfully captured the children's gestures and embodied conduct. However, I underestimated the influence that the noisiness of a classroom of 30 children talking at the same time had on the audio that the cameras would be able to pick up, only to discover that most of the children's conversations were inaudible in the video recordings.

In the second set of classroom studies (presented in Chapter 8) I attempted to solve this problem by providing each pair of children with audio recorders, in addition to just video recording the sessions. However, in the first session I ran for this study, I did not sufficiently stress to the children the importance of keeping the audio recorders turned on and not moving them around. Because of this, a number of the children in this first session used the recorders as a toy, turning them off and on and even singing into them during the session. This meant that much of the required audio data was not recorded, and so, this first session had to be excluded from the analysis.

Furthermore, throughout the research, I faced a number of challenges with data transcription and coding. For example, even after improving the data recording protocol, I found just how challenging it was to pair each child's audio data with their video data. This was because during the studies, children were constantly moving around the classroom, which meant that their voices were recorded by different audio recorders at different times during the session. Moreover, the coding methods employed proved to be very labor intensive; especially for the study presented in Chapter 7, the codes were sometimes micro-seconds in length, as they related to how children shared and took turns with the Magic Cubes. This limited how many pairs of children could be included for full analysis. However, despite this, many interaction patterns were able to be identified which highlighted important aspects of collaborative and embodied learning.

11.4.2 Implications of the methodology for future work

The classification framework of turn taking strategies, and the contexts in which they occur during a discovery task (proposed in Chapter 7), was an outcome that could be generalized to other research investigating how pedagogical approaches influence collaborative exploration of a learning interface. The analytic framing of critical thinking presented in Chapter 8 is also considered a valuable contribution to the learning sciences and educational technology communities. Critical thinking is likely to become increasingly core to computing education, especially as it is considered key to 21st century learning [Partnership for 21st Century Learning, 2019]. The proposed classification system, based on theoretically derived putative cognitive processes involved in critical thinking, presented in this thesis can be a starting point for other researchers who are developing methods for observing and describing the critical thinking processes that take place when learning computing.

11.5 Design Implications

As well as discussing the findings in relation to the three research questions posed in the thesis, this research has led to a number of design implications that can be used to support discovery learning in classroom settings and beyond. These implications are meant to be generalizable and applicable beyond teaching IoT and computing. They are intended to be utilized by others designing interfaces for discovery learning in other domains, for example mathematics or environmental education. I describe these in terms of implications for: *Supporting exploration and understanding; Designing for collaborative discovery;* and *Designing for reflection in discovery learning.*

11.5.1 Supporting exploration and understanding

- *Making tasks open-ended and exploratory, rather than goal based:* A task that is goal based, for example, one where the objective is to obtain a high score, can shift the learner's focus from considering how the technology works, to concentrating just on achieving the goal. In contrast, open-ended tasks where the goal is explicitly to explore how the technology works, can support more reflection.
- *Limiting the number of variables to be discovered:* Starting out with a task that is too complex, where there are too many variables to be discovered, can be frustrating for learners, especially if the technology is unfamiliar to them. A more successful approach can be to begin with simple mappings, and to progressively add other mappings with more complexity.

11.5.2 Designing for collaborative discovery

- *Making actions and effects visible*: Pairing highly physical actions like jumping, reaching, or hiding under tables together with visible effects on an interface enables children to explicitly or implicitly "perform" what they discover to others around the classroom. This in turn can enable them to monitor others around the classroom and in doing so, learn from each other's actions.
- *Enabling turn taking through handheld interfaces*: Interfaces that fit in the hand can support children in negotiating whose turn it is during the learning process, by explicitly handing over or grabbing the interface from others. This type of embodied negotiation can support learners in jointly building, altering and testing hypotheses about the effects to be discovered.

- *Configuring collaboration through the spatial affordances of the task*: Some physical actions, like blowing into a cube, afford interaction by only one person at a time, while others, like hovering a hand above a sensor, enable multiple people to interact together. When designing a discovery task, considering how many people can interact at different points in time, can enable the researcher to configure how much time learners will spend discovering independently or together.

11.5.3 Designing for reflection in discovery learning

- *Providing situated feedback and guidance:* Situated prompts should be designed carefully to provide children with guidance for what to explore in a discovery task. They should also help them build and test new hypotheses as they progress, without giving too much away about what is to be discovered. Asking children reflective questions during a discovery task is also important for enabling them to "step out" of an activity to reflect, in situ, on what they are learning. These types of feedback and guidance are best provided verbally by instructors, but can also be pre-planned and provided through instruction materials.
- *Capitalizing on reflective discussions:* Explicit strategies should be put into place for children to step out of an immersive, hands-on activity in order to reflect on what they are learning. Holding reflective discussions after a discovery activity is one such strategy, that helps children to make connections between the technology they explore and the content to be learned.
- *Making the task personally relevant:* Capitalizing on learning that is tied to a lived experience can help children to more readily reflect on the abstract concepts

to be learned. One strategy that was found promising in this thesis was to design learning activities that utilize children's knowledge of their own bodies as a way to helping them reflect on abstract concepts related to how data is sensed.

11.6 Limitations and Directions for Future Work

11.6.1 The constraints of working with a pre-made toolkit

The Magic Cubes were designed and developed before I began my PhD research. The versatility of the cubes, in terms of how they supported *making*, *discovery* and *coding* activities, provided me with much freedom for exploring how the cubes could be used to best effect to teach IoT topics. I was also able to make a number of alterations to the cubes' functionality throughout the research, for example, by adding new sensors to the cubes, and using them in ways not envisioned when they were initially designed. The benefit of working with an existing toolkit rather than building my own, was that it allowed me to focus much more on evaluating how it supported learning in practice than I would have been able to do otherwise. However, at times, the design of the Magic Cubes also constrained the types of learning activities that I was able to create and investigate. For example, the Magic Cubes are embedded with a classic Bluetooth module, rather than the variety of more recent and powerful wireless connectivity protocols. Because they use the classic Bluetooth protocol, it was not possible for me to create larger wirelessly connected systems of multiple cubes for discovery learning tasks, beyond pairing a few cubes together. Therefore, although initially I was interested in designing activities where, for example, a full classroom of children could collect data and then compare it to one another's through aggregated visualizations, or send data between each other's cubes, the existing Bluetooth hardware meant it was not possible to implement these kinds of activities.

Another aspect that might have changed the activities used with the Magic Cubes was the variety of actuators available for children to explore. Given that the visibility of the light effects on the Magic Cubes was key to much of the collaborative learning that took place in classrooms, it would have been interesting to have explored further whether and how the children's interaction would change if data was actuated in other ways. For example, would the children pay the same level of attention to others around the room, if the sensed data was actuated as music and played through a speaker? Could using sound in lieu of lights make the cubes accessible to visually impaired children? Moreover, what types of playful discovery activities might be possible if the LED lights could be replaced with embedded servo motors that moved the cubes autonomously? This was not possible to do using the existing toolkit. A toolkit with more modular components would have made it possible to create a wider range of activities through which to support learning about IoT.

11.6.2 The constraints of the software

A final constraint of working with the Magic Cubes was the programming environments that were developed for them. Specifically, the text-based Arduino environment, and the visual, block-based ArduBlock environment were designed for creating programs for one cube at a time. However, in these environments, programming two Bluetooth connected cubes was a complex task, requiring a number of abstract steps, like querying the Bluetooth address of a cube, and ensuring that the cubes to be paired had the same baud rate (i.e., that each cube transferred data at the same speed). I hypothesized that these steps would likely disengage children from the broader goal of learning how data is transferred and received between IoT devices. For this reason, I only used the Bluetooth capabilities of the cubes for discovery-based tasks, and did not use them for the coding tasks.

More generally, this raises the question of what is the best software platform to use for learning about IoT? The software created for programming IoT devices thus far has been largely inaccessible to novices – as existing programming environments for physical computing (e.g., Arduino) have not yet been optimized to support learning programming for wirelessly connected devices, or for more than one device at a time. However, in recent years, new programming environments have begun to be developed to enable children to make connections between multiple connected devices in a simpler way. The most notable example is the commercial SAM Labs kit, which provides an intuitive graphical interface where users can simply drag and drop connections between supported hardware components that they want to wirelessly connect together [SAM Labs, n.d.]. By automatically generating text-based code next to these visual, drag-and-drop representations, the interface is also suggested to help learners slowly transition to text-based programming.

11.6.3 The breadth of IoT topics covered

Although this research has outlined a variety of IoT topics that may be appropriate to teach to children just starting to learn about computing, the empirical work that was carried out only addressed a subset of these topics. Specifically, the focus was on teaching children about the functionality of sensors and actuators, as well as about how accurate, reliable and informative sensed data is in different contexts. The study presented in Chapter 9 also demonstrated how it is possible to move from discovery learning to coding, using the same toolkit, however it also primarily focused on the basic IoT topics of sensing, actuation and, to a small extent, teaching children about wireless connectivity.

11.6.4 Limited teacher involvement

Another limitation in this research was that there was little teacher involvement in designing and taking control of the learning activities with the Magic Cubes. This is largely due to the fact that the teachers we worked with had limited time to contribute to the sessions, especially as IoT is not yet on the computing curriculum. Also the cubes were only prototypes and not in a state to hand over to teachers to appropriate in their classes. A number of technical issues that arose when using the Magic Cubes in classrooms, such as errors in the Arduino programming environment, meant there needed to be an expert on hand to fix them.

In sum, teacher involvement in designing IoT learning activities is not straight forward. Some researchers have begun examining the different strategies that teachers employ when using commercially available physical computing toolkits, like the micro:bit, in their classrooms [Sentance, Waite, Yeomans, & MacLeod, 2017]. Others have explored how universities can partner with teachers to support the co-development of open computing education resources for classrooms [Venn-Wycherley & Kharrufa, 2019]. This type of work goes hand in hand with the type of design-oriented research reported in this thesis; it is crucial to capitalize on the skills of teachers, when designing the next generation of physical computing toolkits.

11.6.5 Future work

Future work is needed to address how the discovery learning approach and digital fluency framework developed here can be used to teach the full breadth of IoT topics. Specifically, there is a need to validate whether and how the approaches proposed in this thesis can be applied to topics like learning about how parts in a larger IoT system interact, and the principles of designing privacy into an IoT system. Future work also needs to consider what other kinds of physical toolkits and supporting software platforms can be developed that can effectively build upon the basic building blocks of IoT learning, while also supporting higher level concepts, such as privacy, security, cloud storage and use of different types of networks. To this end, based on the work presented in this thesis, there appears to be much scope for building new interfaces that are able to flexibly support different types of learning, such as making, discovery and coding – in order to simultaneously promote conceptual understanding, critical reflection about IoT and learning how to create IoT objects. A further area of research could also be to consider whether the design implications arising from the research conducted here for learning the basics of IoT are transferable to supporting learning about other new technology paradigms – including Artificial Intelligence, machine learning and big data.

11.7 Conclusions

The research presented in this thesis has shown how to develop discovery learning activities using a physical computing toolkit that can enable children of varying ages and abilities to move between conceptual understanding and critical thinking about the Internet of Things. It has done so by designing different configurations of task complexity, level of scaffolding and opportunities for collaboration, to match the learner group and setting. Rather than viewing coding as the core activity for learning about computing, it was introduced to children as embedded in an integrated set of activities. Instead, the core focus was on discovery learning, which proved to be a powerful way of facilitating the practice of a variety of digital fluency skills – including hypothesis generation, experimentation, explaining, data checking and validating. My PhD research has also shown how it is possible to make learning about computing exciting, fun and importantly be able to provoke children's natural sense of curiosity over a sustained period. Teaching digital fluency involves trusting students to discover for themselves and to experiment with technology in the real world to see its effects, as much as following a lesson. Physical computing can provide the means through which to achieve this, by making it tangible and accessible to all.

REFERENCES

Ackermann, E. (2001). Piaget's constructivism, Papert's constructionism: What's the difference. *Future of Learning Group Publication*, *5*(3), 438.

Ackermann, E. K. (1996). Perspective-Taking and Object Construction: Two Keys to Learning. In *Constuctionism in Practice: Designing, Thinking, and Learning in a Digital World (Kafai, Y., and Resnick, M., Eds.).* (pp. 25–37). Mahwah, New Jersey: Lawrence Erlbaum Associates. Part 1, Chapter 2.

Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology*, *103*(1), 1–18. https://doi.org/10.1037/a0021017

Ali, F. (2015). Teaching the internet of things concepts. *Proceedings of the WESE'15: Workshop on Embedded and Cyber-Physical Systems Education*, 10. ACM.

Antle, A. N. (2009). LIFELONG INTERACTIONS Embodied child computer interaction: Why embodiment matters. *Interactions*, *16*(2), 27–30.

Antle, A. N. (2013). Research opportunities: Embodied child–computer interaction. *International Journal of Child-Computer Interaction*, *1*(1), 30–36. https://doi.org/10.1016/j.ijcci.2012.08.001

Antle, A. N., & Wise, A. F. (2013). Getting Down to Details: Using Theories of Cognition and Learning to Inform Tangible User Interface Design. *Interacting with Computers*, *25*(1), 1–20. https://doi.org/10.1093/iwc/iws007

Ardublock. (n.d.). Retrieved May 24, 2019, from http://blog.ardublock.com/

Arduino. (n.d.). Arduino. Retrieved September 6, 2017, from https://www.arduino.cc/

Astin, A. W. (1984). Student involvement: A developmental theory for higher education. *Journal of College Student Personnel*, *25*(4), 297–308.

Baauw, E., & Markopoulous, P. (2004). A comparison of think-aloud and post-task interview for usability testing with children. *Proceedings of the 2004 Conference on Interaction Design and Children: Building a Community*, 115–116. ACM.

Bailin, S., Case, R., Coombs, J. R., & Daniels, L. B. (1999). Common misconceptions of critical thinking. *Journal of Curriculum Studies*, *31*(3), 269–283.

Bailin, S., & Siegel, H. (2002). Critical thinking. *The Blackwell Guide to the Philosophy of Education*, 181–193.

Baker, S., Dekov, S., Fakih, F., Medvesek, J., Shum, V., & Mohamedally, D. (2014). Supporting Situated STEM Learning: TouchDevelop Integration of the UCL Engduino over Bluetooth. *Proceedings of the 2Nd Workshop on Programming for Mobile & Touch*, 17–20. https://doi.org/10.1145/2688471.2688477

Bar-El, D., Zuckerman, O., & Shlomi, Y. (2016). Social Competence and STEM: Teen Mentors in a Makerspace. *Proceedings of the The 15th International Conference on Interaction Design and Children*, 595–600. ACM.

Bdeir, A. (2009). Electronics as material: LittleBits. *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, 397–400. Retrieved from http://dl.acm.org/citation.cfm?id=1517743

Beginner's Mind Collective, & Shaw, D. (2012). Makey Makey: Improvising tangible and nature-based user interfaces. *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, 367–370. ACM.

Benton, L., Vasalou, A., Barendregt, W., Bunting, L., & Revesz, A. (2019). What's Missing: The Role of Instructional Design in Children's Games-Based Learning. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 582. ACM.

Blikstein, P. (2013). Digital fabrication and 'making'in education: The democratization of invention. *FabLabs: Of Machines, Makers and Inventors*, *4*, 1–21.

Blikstein, P. (2015). Computationally enhanced toolkits for children: Historical review and a framework for future design. *Foundations and Trends® in Human–Computer Interaction*, *9*(1), 1–68.

Blikstein, P. (2019). Project Bloks: Embodied and Collaborative Learning with Tangible Interfaces for Young Children. *A Wide Lens: Combining Embodied, Enactive, Extended, and Embedded Learning in Collaborative Settings*.

Blikstein, P., Sipitakiat, A., Goldstein, J., Wilbert, J., Johnson, M., Vranakis, S., ... Carey, W. (2016). Project Bloks: Designing a development platform for tangible programming for children. *Position Paper, Retrieved Online On*, 06–30.

Börjesson, P., Barendregt, W., Eriksson, E., & Torgersson, O. (2015). Designing Technology for and with Developmentally Diverse Children: A Systematic Literature Review. *Proceedings of the 14th International Conference on Interaction Design and Children*, 79–88. https://doi.org/10.1145/2771839.2771848

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brennan, K., & Resnick, M. (2012). New frameworks for studying and assessing the development of computational thinking. *Proceedings of the 2012 Annual Meeting of the American Educational Research Association, Vancouver, Canada*, *1*, 25.

Bruck, M., & Ceci, S. J. (1999). The suggestibility of children's memory. *Annual Review of Psychology*, *50*(1), 419–439.

Bruner, J. S. (1961). The act of discovery. *Harvard Educational Review*, *31*, 21–32.

Buechley, L., Eisenberg, M., Catchen, J., & Crockett, A. (2008). The LilyPad Arduino: Using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 423–432. ACM.

Burd, B., Barker, L., Divitini, M., Perez, F. A. F., Russell, I., Siever, B., & Tudor, L. (2018). Courses, content, and tools for internet of things in computer science education. *Proceedings of the 2017 ITiCSE Conference on Working Group Reports*, 125–139. ACM.

Cisco Systems. (2013). *Connections counter: The Internet of Everything in motion*. Retrieved from http:// newsroom.cisco.com/feature-content?articleId=1208342

Cohen, J., Jones, W. M., Smith, S., & Calandra, B. (2017). Makification: Towards a framework for leveraging the maker movement in formal education. *Journal of Educational Multimedia and Hypermedia*, *26*(3), 217–229.

Computing At School Working Group. (2009). *Computing at School: The State of the Nation*.

Corno, L., & Mandinach, E. B. (1983). The role of cognitive engagement in classroom learning and motivation. *Educational Psychologist*, *18*(2), 88–108.

Creative Commons. (n.d.). Retrieved May 24, 2019, from https://creativecommons.org/

CS4ALL Blueprint Beta. (n.d.). Retrieved May 24, 2019, from CS4All Blueprint—Beta website: https://blueprint.cs4all.nyc/

Dasgupta, S. (2013). From Surveys to Collaborative Art: Enabling Children to Program with Online Data. *Proceedings of the 12th International Conference on Interaction Design and Children*, 28–35. https://doi.org/10.1145/2485760.2485784

Dasgupta, S., & Hill, B. M. (2017). Scratch community blocks: Supporting children as data scientists. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 3620–3631. ACM.

Dasgupta, S., & Resnick, M. (2014). Engaging Novices in Programming, Experimenting, and Learning with Data. *ACM Inroads*, *5*(4), 72–75. https://doi.org/10.1145/2684721.2684737

Davis, R. L., Schneider, B., & Blikstein, P. (2017). *Making the invisible visible: A new method for capturing student development in makerspaces*. Philadelphia, PA: International Society of the Learning Sciences.

Department for Education. (2019). *Special education needs in England: January 2019*. Retrieved from Department for Education, HM Government website: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/814244/SEN_2019_Text.docx.pdf

Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., … Sherin, B. L. (2010). Conducting Video Research in the Learning Sciences: Guidance on Selection, Analysis, Technology, and Ethics. *Journal of the Learning Sciences*, *19*(1), 3–53. https://doi.org/10.1080/10508400903452884

Dewey, J. (1902). *The child and the curriculum*. University of Chicago Press.

Dillenbourg, P. (1999). *What do you mean by collaborative learning?* Oxford: Elsevier.

DiSessa, A. A. (2001). *Changing minds: Computers, learning, and literacy*. Mit Press.

Donker, A., & Reitsma, P. (2004). Usability testing with young children. *Proceedings of the 2004 Conference on Interaction Design and Children: Building a Community*, 43–48. ACM.

Dourish, P. (2004). *Where the action is: The foundations of embodied interaction*. MIT press.

Druin, A. (2002). The role of children in the design of new technology. *Behaviour and Information Technology*, *21*(1), 1–25.

Engduino. (n.d.). Engduino. Retrieved May 24, 2019, from http://www.engduino.org/html/index.html

Ennis, R. H. (1985). A logical basis for measuring critical thinking skills. *Educational Leadership*, *43*(2), 44–48.

Facione, P. (1990). *Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction (The Delphi Report).*

Falcão, T. P., & Price, S. (2010). Informing design for tangible interaction: A case for children with learning difficulties. *Proceedings of the 9th International Conference on Interaction Design and Children*, 190–193. Retrieved from http://dl.acm.org/citation.cfm?id=1810568

Farr, W., Yuill, N., & Raffle, H. (2010). Social benefits of a tangible user interface for children with Autistic Spectrum Conditions. *Autism*, *14*(3), 237–252. https://doi.org/10.1177/1362361310363280

Feaster, Y., Zhai, J., & Hallstrom, J. O. (2015). Serious toys: Introducing sensors and sensor networks in pre-collegiate classrooms. *Proceedings of the 16th Annual Conference on Information Technology Education*, 3–8. ACM.

Fleck, R., Rogers, Y., Yuill, N., Marshall, P., Carr, A., Rick, J., & Bonnett, V. (2009). Actions Speak Loudly with Words: Unpacking Collaboration Around the Table. *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, 189–196. https://doi.org/10.1145/1731903.1731939

Frei, P., Su, V., Mikhak, B., & Ishii, H. (2000). Curlybot: Designing a new class of computational toys. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 129–136. ACM.

Freire, P. (1973). *Education for critical consciousness* (Vol. 1). Bloomsbury Publishing.

Garrison, D. R. (1992). Critical thinking and self-directed learning in adult education: An analysis of responsibility and control issues. *Adult Education Quarterly*, *42*(3), 136–148.

Gershenfeld, N. (2008). *Fab: The coming revolution on your desktop–from personal computers to personal fabrication*. Basic Books.

Goodwin, C., & Heritage, J. (1990). Conversation analysis. *Annual Review of Anthropology*, *19*(1), 283–307.

Hall, T., & Bannon, L. (2006). Designing ubiquitous computing to enhance children's learning in museums. *Journal of Computer Assisted Learning*, *22*(4), 231–243.

Halpern, D. F. (1992). A Cognitive Approach to Improving Thinking Skills in the Sciences and Mathematics. *Enhancing Thinking Skills in the Sciences and Mathematics*.

Harbird, R., Barbareschi, G., Makrygianni, E., Holloway, C., & Hailes, S. (2017). Fleas, Caterpillars and Cockroaches: A Summer School in Bio-inspired Robotics. *IEEE Global Engineering Education Conference, EDUCON 2017*, *2017*. IEEE.

Heath, C., Hindmarsh, J., & Luff, P. (2010). *Video in Qualitative Research*. SAGE.

Hitron, T., Orlev, Y., Wald, I., Shamir, A., Erel, H., & Zuckerman, O. (2019). *Can Children Understand Machine Learning Concepts? The Effect of Uncovering Black Boxes*.

Hmelo, C. E., & Guzdial, M. (1996). Of Black and Glass Boxes: Scaffolding for Doing and Learning. *Proceedings of the 1996 International Conference on Learning Sciences*, 128–134. Retrieved from http://dl.acm.org/citation.cfm?id=1161135.1161153

Holbert, N. (2016). Bots for Tots: Building Inclusive Makerspaces by Leveraging Ways of Knowing. *Proceedings of the The 15th International Conference on Interaction Design and Children*, 79–88. ACM.

Holt, S., & Yuill, N. (2014). Facilitating other-awareness in low-functioning children with autism and typically-developing preschoolers using dual-control technology. *Journal of Autism and Developmental Disorders*, *44*(1), 236–248.

Horn, M. S., Brady, C., Hjorth, A., Wagh, A., & Wilensky, U. (2014). Frog pond: A codefirst learning environment on evolution and natural selection. *Proceedings of the 2014 Conference on Interaction Design and Children*, 357–360. ACM.

Horn, M. S., Crouser, R. J., & Bers, M. U. (2012). Tangible Interaction and Learning: The Case for a Hybrid Approach. *Personal Ubiquitous Comput.*, *16*(4), 379–389. https://doi.org/10.1007/s00779-011-0404-2

Horn, M. S., & Jacob, R. J. (2007). Tangible programming in the classroom with tern. *CHI'07 Extended Abstracts on Human Factors in Computing Systems*, 1965–1970. ACM.

Horn, M. S., Solovey, E. T., Crouser, R. J., & Jacob, R. J. (2009). Comparing the use of tangible and graphical programming languages for informal science education. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 975–984. Retrieved from http://dl.acm.org/citation.cfm?id=1518851

Hornecker, E., & Buur, J. (2006). Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 437–446. https://doi.org/10.1145/1124772.1124838

Hutchins, E. (1995). *Cognition in the Wild*. MIT Press.

Ishii, H., & Ullmer, B. (1997). Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. *Proceedings of the ACM Conference on Human Factors in Computing Systems*, 234–241. http://dx.doi.org/10.1145/258549.258715

Israel, M., Pearson, J. N., Tapia, T., Wherfel, Q. M., & Reese, G. (2015). Supporting all learners in school-wide computational thinking: A cross-case qualitative analysis. *Computers & Education*, *82*, 263–279.

Israel, M., Wherfel, Q. M., Pearson, J., Shehab, S., & Tapia, T. (2015). Empowering K-12 students with disabilities to learn computational thinking and computer programming. *TEACHING Exceptional Children*, *48*(1), 45–53.

Jacob, R. J., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., & Zigelbaum, J. (2008). Reality-based interaction: A framework for post-WIMP interfaces. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 201–210. ACM.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences*, *15*(1), 11–34.

Johnson, R., Shum, V., Rogers, Y., & Marquardt, N. (2016). Make or Shake: An Empirical Study of the Value of Making in Learning About Computing Technology. *Proceedings of the The 15th International Conference on Interaction Design and Children*, 440–451. https://doi.org/10.1145/2930674.2930691

Jokela, T., Iivari, N., Matero, J., & Karukka, M. (2003). The standard of user-centered design and the standard definition of usability: Analyzing ISO 13407 against

ISO 9241-11. *Proceedings of the Latin American Conference on Human-Computer Interaction*, 53–60. ACM.

Jordan, B., & Henderson, A. (1995). Interaction Analysis: Foundations and Practice. *Journal of the Learning Sciences*, *4*(1), 39–103. https://doi.org/10.1207/s15327809jls0401_2

Kafai, Y. B. (2002). Constructionism. In *The Cambridge Handbook of the Learning Sciences*. Cambridge University Press.

Kafai, Y. B., & Peppler, K. A. (2014). 12 Transparency Reconsidered: Creative, Critical, and Connected Making with E-textiles. *DIY Citizenship: Critical Making and Social Media*, 179.

Klemmer, S. R., Hartmann, B., & Takayama, L. (2006). How Bodies Matter: Five Themes for Interaction Design. *Proceedings of the 6th Conference on Designing Interactive Systems*, 140–149. https://doi.org/10.1145/1142405.1142429

Kortuem, G., Bandara, A. K., Smith, N., Richards, M., & Petre, M. (2012). Educating the Internet-of-Things generation. *Computer*, *46*(2), 53–61.

Koushik, V., & Kane, S. K. (2019). " It Broadens My Mind": Empowering People with Cognitive Disabilities through Computing Education. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 514. ACM.

Kumar, P., Vitak, J., Chetty, M., Clegg, T. L., Yang, J., McNally, B., & Bonsignore, E. (2018). Co-designing Online Privacy-related Games and Stories with Children. *Proceedings of the 17th ACM Conference on Interaction Design and Children*, 67–79. https://doi.org/10.1145/3202185.3202735

Lai, E. R. (2011). Critical thinking: A literature review. *Pearson's Research Reports*, *6*, 40–41.

Lakanen, A.-J. (2016). On the impact of computer science outreach events on K-12 students. *Jyväskylä Studies in Computing*, (236).

Lang, C., Craig, A., & Casey, G. (2017). A pedagogy for outreach activities in ICT: Promoting peer to peer learning, creativity and experimentation. *British Journal of Educational Technology*, *48*(6), 1491–1501.

Lee, E., Kafai, Y. B., Vasudevan, V., & Davis, R. L. (2014). Playing in the arcade: Designing tangible interfaces with MaKey MaKey for Scratch games. In *Playful user interfaces* (pp. 277–292). Springer.

Livingstone, I., & Hope, A. (2011). Next Gen: Transforming the UK into the world's leading talent hub for the video games and visual effects industries. *National Endowment for Science, Technology and the Arts (NESTA), London, UK.*

Logo Foundation. (n.d.). Logo History. Retrieved July 1, 2019, from https://el.media.mit.edu/logo-foundation/what_is_logo/history.html

Lu, J. J., & Fletcher, G. H. (2009). Thinking about computational thinking. *ACM SIGCSE Bulletin*, *41*, 260–264. ACM.

Lyons, L., Tissenbaum, M., Berland, M., Eydt, R., Wielgus, L., & Mechtley, A. (2015). Designing Visible Engineering: Supporting Tinkering Performances in Museums. *Proceedings of the 14th International Conference on Interaction Design and Children*, 49–58. https://doi.org/10.1145/2771839.2771845

Maquil, V., Moll, C., Schwartz, L., & Hermen, J. (2018). Kniwwelino: A Lightweight and WiFi Enabled Prototyping Platform for Children. *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, 94–100. ACM.

Markopoulos, P., & Bekker, M. (2003). On the assessment of usability testing methods for children. *Interacting with Computers*, *15*(2), 227–243. https://doi.org/10.1016/S0953-5438(03)00009-2

Marks, H. M. (2000). Student engagement in instructional activity: Patterns in the elementary, middle, and high school years. *American Educational Research Journal*, *37*(1), 153–184.

Marquardt, N., Lechelt, Z., Rogers, Y., & Shum, V. (n.d.). UCL Magic Cubes. Retrieved May 24, 2019, from UCL Magic Cubes website: http://uclmagiccube.weebly.com/

Marshall, P. (2007). Do Tangible Interfaces Enhance Learning? *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, 163–170. https://doi.org/10.1145/1226969.1227004

Marshall, P., Cheng, P. C.-H., & Luckin, R. (2010). Tangibles in the balance: A discovery learning task with physical or graphical materials. *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*, 153–160. ACM.

Marshall, P., Fleck, R., Harris, A., Rick, J., Hornecker, E., Rogers, Y., ... Dalton, N. S. (2009). Fighting for Control: Children's Embodied Interactions when Using Physical and Digital Representations. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2149–2152. https://doi.org/10.1145/1518701.1519027

Marshall, P., Price, S., & Rogers, Y. (2003). Conceptualising tangibles to support learning. *Proceedings of the 2003 Conference on Interaction Design and Children*, 101–109. ACM.

Martin, F., Mikhak, B., Resnick, M., Silverman, B., & Berg, R. (2000). To mindstorms and beyond. *Robots for Kids: Exploring New Technologies for Learning*, 9–33.

Matias, J. N., Dasgupta, S., & Hill, B. M. (2016). Skill Progression in Scratch Revisited. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 1486–1490. https://doi.org/10.1145/2858036.2858349

Mayer, R. E. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist*, *59*(1), 14.

Melcer, E. F., Hollis, V., & Isbister, K. (2017). Tangibles vs. Mouse in Educational Programming Games: Influences on Enjoyment and Self-Beliefs. *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 1901–1908. ACM.

Melcer, E. F., & Isbister, K. (2016). Bridging the physical divide: A design framework for embodied learning games and simulations. *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 2225–2233. ACM.

Melcer, E. F., & Isbister, K. (2018). Bots & (Main) Frames: Exploring the impact of tangible blocks and collaborative play in an educational programming game. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 266. ACM.

Micro:bit. (n.d.). Micro:bit Educational Foundation. Retrieved November 3, 2019, from https://microbit.org/

Mikhak, B., Lyon, C., Gorton, T., Gershenfeld, N., McEnnis, C., & Taylor, J. (2002). Fab Lab: An alternate model of ICT for development. *2nd International Conference on Open Collaborative Design for Sustainable Innovation*, 1–7.

Morrison, C., Villar, N., Thieme, A., Ashktorab, Z., Taysom, E., Salandin, O., ... Edge, D. (2018). Torino: A tangible programming language inclusive of children with visual disabilities. *Human–Computer Interaction*, 1–49.

National Research Council. (1999). *Funding a revolution: Government support for computing research*. National Academies Press.

Newman, D. R., Johnson, C., Webb, B., & Cochrane, C. (1997). Evaluating the quality of learning in computer supported co-operative learning. *Journal of the American Society for Information Science*, *48*(6), 484–495.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Retrieved from http://dl.acm.org/citation.cfm?id=1095592

Paris, S. G., & Hapgood, S. E. (2002). Children learning with objects in informal learning environments. *Perspectives on Object-Centered Learning in Museums*, 37–54.

Parkes, A. J., Raffle, H. S., & Ishii, H. (2008). Topobo in the wild: Longitudinal evaluations of educators appropriating a tangible interface. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1129–1138. ACM.

Partnership for 21st Century Learning. (2019). *21st Century Learning for Early Childhood Framework*. Retrieved from http://www.battelleforkids.org/networks/p21/frameworks-resources

Pearson, G., & Young, T. (2002). *Technically speaking: Why all Americans need to know more about technology*. National Academies Press.

Piaget, J. (2013). *The construction of reality in the child* (Vol. 82). Routledge.

Porcheron, M., Fischer, J. E., Reeves, S., & Sharples, S. (2018). Voice interfaces in everyday life. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 640. ACM.

Portelance, D. J., & Bers, M. U. (2015). Code and Tell: Assessing young children's learning of computational thinking using peer video interviews with ScratchJr. *Proceedings of the 14th International Conference on Interaction Design and Children*, 271–274. Retrieved from http://dl.acm.org/citation.cfm?id=2771894

Price, S., & Falcão, T. P. (2011). Where the attention is: Discovery learning in novel tangible environments. *Interacting with Computers*, *23*(5), 499–512.

Price, S., Falcão, T. P., Sheridan, J. G., & Roussos, G. (2009). The effect of representation location on interaction in a tangible learning environment. *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, 85–92. ACM.

Price, S., & Rogers, Y. (2004). Let's get physical: The learning benefits of interacting in digitally augmented physical spaces. *Computers & Education*, *43*(1–2), 137–151.

Quinlan, O. (2015). Young digital makers. *London: Nesta.*

Raffle, H. S., Parkes, A. J., & Ishii, H. (2004). Topobo: A constructive assembly system with kinetic memory. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 647–654. ACM.

Raspberry Pi. (n.d.). Raspberry Pi—Teach, Learn, and Make with Raspberry Pi. Retrieved from Raspberry Pi website: https://www.raspberrypi.org/

Read, J. C. (2008). Validating the Fun Toolkit: An instrument for measuring children's opinions of technology. *Cognition, Technology & Work*, *10*(2), 119–128.

Read, J. C., MacFarlane, S., & Casey, C. (2002). Endurability, engagement and expectations: Measuring children's fun. *Interaction Design and Children*, *2*, 1–23. Shaker Publishing Eindhoven.

Resnick, M. (1997). *Turtles, termites, and traffic jams: Explorations in massively parallel microworlds*. Mit Press.

Resnick, M. (1998). Technologies for lifelong kindergarten. *Educational Technology Research and Development*, *46*(4), 43–55.

Resnick, M. (2002). *Rethinking learning in the digital age*. The global information technology report: Readiness for the networked world. Oxford University Press.

Resnick, M. (2006). Computer as paint brush: Technology, play, and the creative society. *Play= Learning: How Play Motivates and Enhances Children's Cognitive and Social-Emotional Growth*, 192–208.

Resnick, M. (2012). *Mother's Day, Warrior Cats, and Digital Fluency: Stories from the Scratch Online Community*. 7.

Resnick, M., Maloney, J., Monroy-Hernández, A., Rusk, N., Eastmond, E., Brennan, K., ... Silverman, B. (2009). Scratch: Programming for all. *Communications of the ACM*, *52*(11), 60–67.

Resnick, M., & Ocko, S. (1990). *LEGO/logo–learning through and about design*. Epistemology and Learning Group, MIT Media Laboratory Cambridge, MA.

Richmond, B., & Peterson, S. (2001). *An introduction to systems thinking*. High Performance Systems., Incorporated.

Rogers, Y., Price, S., Fitzpatrick, G., Fleck, R., Harris, E., Smith, H., ... Weal, M. (2004). Ambient Wood: Designing New Forms of Digital Augmentation for Learning Outdoors. *Proceedings of the 2004 Conference on Interaction Design and Children: Building a Community*, 3–10. https://doi.org/10.1145/1017833.1017834

Rogers, Yvonne. (2011). Interaction design gone wild: Striving for wild theory. *Interactions*, *18*(4), 58. https://doi.org/10.1145/1978822.1978834

Rogers, Yvonne, & Brignull, H. (2002). Subtle ice-breaking: Encouraging socializing and interaction around a large public display. *Workshop on Public, Community. and Situated Displays*, 6. Citeseer.

Rogers, Yvonne, Connelly, K., Tedesco, L., Hazlewood, W., Kurtz, A., Hall, R. E., ... Toscos, T. (2007). Why It's Worth the Hassle: The Value of In-Situ Studies

When Designing Ubicomp. In J. Krumm, G. D. Abowd, A. Seneviratne, & T. Strang (Eds.), *UbiComp 2007: Ubiquitous Computing* (pp. 336–353). Springer Berlin Heidelberg.

Rogers, Yvonne, & Marshall, P. (2017). Research in the Wild. *Synthesis Lectures on Human-Centered Informatics*, *10*(3), i–97. https://doi.org/10.2200/S00764ED1V01Y201703HCI037

Rogers, Yvonne, & Muller, H. (2006). A framework for designing sensor-based interactions to promote exploration and reflection in play. *International Journal of Human-Computer Studies*, *64*(1), 1–14.

Rogers, Yvonne, Price, S., Harris, E., Phelps, T., Underwood, M., Wilde, D., … Neale, H. (2002). *Learning through digitally-augmented physical experiences: Reflections on the ambient wood project.*

Rogers, Yvonne, Scaife, M., Gabrielli, S., Smith, H., & Harris, E. (2002). A Conceptual Framework for Mixed Reality Environments: Designing Novel Learning Activities for Young Children. *Presence: Teleoper. Virtual Environ.*, *11*(6), 677–686. https://doi.org/10.1162/105474602321050776

Rogers, Yvonne, Shum, V., Marquardt, N., Lechelt, S., Johnson, R., Baker, H., & Davies, M. (2017). From the BBC Micro to micro: Bit and Beyond: A British Innovation. *Interactions*, *24*(2), 74–77.

Roschelle, J., & Teasley, S. D. (1995). The Construction of Shared Knowledge in Collaborative Problem Solving. In C. O'Malley (Ed.), *Computer Supported Collaborative Learning* (pp. 69–97). https://doi.org/10.1007/978-3-642-85098-1_5

Rosenshine, B. (2009). The Empirical Support for Direct Instruction. *Constructivist Instruction*, 201.

Rusk, N., Resnick, M., & Cooke, S. (2009). Origins and guiding principles of the computer clubhouse. *The Computer Clubhouse: Constructionism and Creativity in Youth Communities*, 17–25.

SAM Labs. (n.d.). Sam Labs: Discover the fun in STEAM and coding in your classroom. Retrieved September 1, 2019, from https://samlabs.com

Schneider, B., Bumbacher, E., & Blikstein, P. (2015). Discovery versus direct instruction: Learning outcomes of two pedagogical models using tangible interfaces. *Exploring the Material Conditions of Learning: Opportunities and Challenges for CSCL," the Proceedings of the Computer Supported Collaborative Learning (CSCL) Conference*, *1*, 364–371.

Scratch—Micro:bit. (n.d.). Retrieved July 4, 2019, from https://scratch.mit.edu/

Scratch—WeDo 2.0. (n.d.). Retrieved July 4, 2019, from https://scratch.mit.edu/wedo

Sentance, S., Waite, J., Hodges, S., MacLeod, E., & Yeomans, L. (2017). Creating Cool Stuff: Pupils' Experience of the BBC micro: bit. *Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education*, 531–536. ACM.

Sentance, S., Waite, J., Yeomans, L., & MacLeod, E. (2017). Teaching with physical computing devices: The BBC micro: bit initiative. *Proceedings of the 12th Workshop on Primary and Secondary Computing Education*, 87–96. ACM.

Sharp, H., Rogers, Y., & Preece, J. (2019). *Interaction Design: Beyond human-computer interaction*. Wiley.

Sim, G., MacFarlane, S., & Read, J. (2006). All work and no play: Measuring fun, usability, and learning in software for children. *Computers & Education*, *46*(3), 235–248. https://doi.org/10.1016/j.compedu.2005.11.021

Sipitakiat, A., & Nusen, N. (2012). Robo-Blocks: Designing debugging abilities in a tangible programming system for early primary school children. *Proceedings of the 11th International Conference on Interaction Design and Children*, 98–105. ACM.

Somanath, S., Oehlberg, L., Hughes, J., Sharlin, E., & Sousa, M. C. (2017). 'Maker'within constraints: Exploratory study of young learners using Arduino at a high school in India. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 96–108. ACM.

Sparrow, J. (2018). Digital Fluency: Preparing Students to Create Big, Bold Problems. Retrieved September 6, 2019, from https://er.educause.edu/articles/2018/3/digital-fluency-preparing-students-to-create-big-bold-problems

Speelpenning, T., Antle, A. N., Doering, T., & Hoven, E. van den. (2011). Exploring How Tangible Tools Enable Collaboration in a Multi-touch Tabletop Game. In P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, & M. Winckler (Eds.), *Human-Computer Interaction – INTERACT 2011* (pp. 605–621). https://doi.org/10.1007/978-3-642-23771-3_45

Stahl, G., Koschmann, T. D., & Suthers, D. D. (2006). *Computer-supported collaborative learning*. na.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research techniques*. Sage publications Thousand Oaks, CA.

Strawhacker, A., & Bers, M. U. (2015). "I want my robot to look for food": Comparing Kindergartner's programming comprehension using tangible, graphic, and hybrid user interfaces. *International Journal of Technology and Design Education*, *25*(3), 293–319.

Suzuki, H., & Kato, H. (1995). Interaction-level Support for Collaborative Learning: AlgoBlock—an Open Programming Language. *The First International Conference on Computer Support for Collaborative Learning*, 349–355. https://doi.org/10.3115/222020.222828

Szyd\lo, T., Brzoza-Woch, R., & Konieczny, M. (2018). The Copernicus IoT platform: Teaching IoT at Computer Science case study. *IFAC-PapersOnLine*, *51*(6), 144–149.

Tech Will Save Us. (n.d.). Tech Will Save Us. Retrieved September 1, 2019, from https://www.techwillsaveus.com/

Thieme, A., Morrison, C., Villar, N., Grayson, M., & Lindley, S. (2017). Enabling collaboration in learning computer programing inclusive of children with vision impairments. *Proceedings of the 2017 Conference on Designing Interactive Systems*, 739–752. ACM.

Tisue, S., & Wilensky, U. (2004). Netlogo: A simple environment for modeling complexity. *International Conference on Complex Systems*, *21*, 16–21. Boston, MA.

Trilling, B., & Fadel, C. (2009). *21st century skills: Learning for life in our times*. John Wiley & Sons.

UK Department of Education. (2016, June). National curriculum in England: Design and technology programmes of study - GOV.UK. Retrieved from https://www.gov.uk/government/publications/national-curriculum-in-england-design-and-technology-programmes-of-study/national-curriculum-in-england-design-and-technology-programmes-of-study

UK Government Office for Science. (2014). *The Internet of Things: Making most of the Second Digital Revolution*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/409774/14-1230-internet-of-things-review.pdf

van Laar, E., van Deursen, A. J. A. M., van Dijk, J. A. G. M., & de Haan, J. (2017). The relation between 21st-century skills and digital skills: A systematic literature review. *Computers in Human Behavior*, *72*, 577–588. https://doi.org/10.1016/j.chb.2017.03.010

Venn-Wycherley, M., & Kharrufa, A. (2019). HOPE for Computing Education: Towards the Infrastructuring of Support for University-School Partnerships. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 499. ACM.

Villar, N., Scott, J., Hodges, S., Hammil, K., & Miller, C. (2012). . net gadgeteer: A platform for custom devices. *International Conference on Pervasive Computing*, 216–233. Springer.

Virnes, M., Sutinen, E., & Kärnä-Lin, E. (2008). How Children's Individual Needs Challenge the Design of Educational Robotics. *Proceedings of the 7th International Conference on Interaction Design and Children*, 274–281. https://doi.org/10.1145/1463689.1463766

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Wardrip, P. S., & Brahms, L. (2015). Learning practices of making: Developing a framework for design. *Proceedings of the 14th International Conference on Interaction Design and Children*, 375–378. ACM.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology*, *8*(1), 3–19.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, *49*(3), 33–35.

Wise, A. F., Antle, A. N., Warren, J., May, A., Fan, M., & Macaranas, A. (2015). *What kind of world do you want to live in? Positive interdependence and collaborative processes in the tangible tabletop land-use planning game Youtopia*. International Society of the Learning Sciences, Inc.[ISLS].

World Economic Forum. (2018). *The Future of Jobs Report*. Retrieved from http://www3.weforum.org/docs/WEF_Future_of_Jobs_2018.pdf

Yuill, N., & Rogers, Y. (2012). Mechanisms for Collaboration: A Design and Evaluation Framework for Multi-user Interfaces. *ACM Trans. Comput.-Hum. Interact.*, *19*(1), 1:1–1:25. https://doi.org/10.1145/2147783.2147784

Zaman, B., Abeele, V. V., Markopoulos, P., & Marshall, P. (2011). Editorial: The evolving field of tangible interaction for children: the challenge of empirical validation. *Personal and Ubiquitous Computing*, *16*(4), 367–378. https://doi.org/10.1007/s00779-011-0409-x

Zuckerman, O., Arida, S., & Resnick, M. (2005). Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 859–868. https://doi.org/10.1145/1054972.1055093

Zuckerman, O., & Gal-Oz, A. (2013). To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces. *International Journal of Human-Computer Studies*, *71*(7–8), 803–820.

APPENDIX A: IDEATION WORKSHOP MATERIALS

A.1 The pre-test provided to the participants

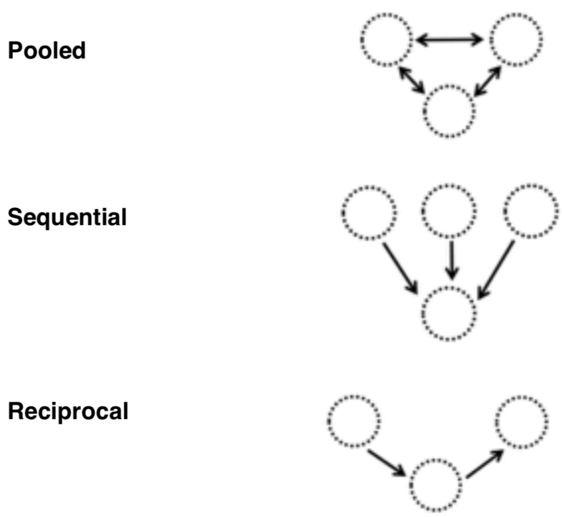
The participants were asked to fill in the pre-test on paper. The questions were as follows:

Q1. What is interdependence?

Q2. What does co-operation mean?

Q3. What are some examples of co-operation in the real world?

Q4. Can you match the drawings and names of different types of interdependence? (Note: here, the circles are the "parts" and the arrows are the "connections" between parts.)



Q5. In the space below, draw a system in the real world. This could be, for example, a car or a bike, but feel free to get creative! You can draw a natural system, an engineered system or even a social system.

Q5 B. Cross out one of the parts of the system you just drew. Describe what will happen to how the system works if the part you crossed out were taken away. Why will this happen?

A.2 The post-test provided to the participants

The participants were provided with the post-test on paper. The questions were the identical to those in the pre-test, with the exception of Q5, which was replaced with:

Q5. In the space below, draw our "system" of cubes from activity 2. Represent the "parts" as circles and the "connections" between the parts as arrows. Label your drawing.

Q5 B. Can you explain how the cubes interacted together in activity 2?

A.3 The activity sheet provided to the participants

The participants were presented with the following guidance for the two activities that they were asked to complete. The aim of this guidance was to help them explore and discovery task-relevant variables in the Magic Cubes.

Activity 1: Mutual Cooperation

Step 1: Explore

Get together with your partner, and shake one of your cubes at a time. What is happening?

Now, collaborate with your partner and shake both of your cubes at the same time.

Did anything change in either or both of the cubes?

Step 2: Discuss and Reflect

How did the two cubes change when they were shaken together?

Can you think of any examples in the real world where the action of one thing can influence another? How about any examples where one thing can make another stronger?

How else do you think the cubes could collaborate together?

Activity 2: Wheel of Interdependencee

Step 1: Explore

Together with a partner, explore what effect pushing the yellow user button has on the cubes.

What happens when the button is pushed on one of the cubes at a time?

How about when the buttons on both cubes are pushed at the same time?

Does pushing the buttons on both cubes at the same time over and over again change anything?

Does the speed at which you and your partner push the buttons change anything?

Step 2: Discuss and Reflect

What did the buttons do to the animation?

What changed when the button on only one cube was pushed?

Can you think of any examples in the real world where something works only when all of its parts are functioning?

APPENDIX B: FIELD JOURNALS TO SUPPORT DISCOVERY OF SENSORS AND SENSING

This appendix includes the "field journal" designed for Chapter 8 and provided to the children in the study.

MY

MAGIC CUBES

FIELD JOURNAL

Learning about sensors and data

School: ______________________________

Name: ______________________________

Age: ______________________________

I am a: Boy / Girl / Rather not say (Circle one)

ACTIVITY 1: THINKING ABOUT SENSORS

Answer these after the discussion

What is a sensor?

____

____

____

What kinds of “sensors” does your body have?

(example: skin for sensing touch)

____

____

____

What are examples of sensors that computers and digital devices can have?

(example: microphone for sensing sound)

____

____

____

ACTIVITY 2: DISCOVERING THE PEDOMETER

First, attach the cube to your foot using the velcro strap. Now try walking around the room and count the number of steps you take.

Does the number of steps match how many steps you actually took?

YES NO

Now try attaching the cube somewhere else on your body (for example, to your thigh, or to your hip, or holding it in your hand). Does the pedometer give you the correct number of steps?

YES NO

Does your step count change if you take bigger/smaller steps? What if you jump instead of walk?

YES NO

When the pedometer got the number of steps wrong, why do you think it happened?

____

____

____

Try to trick the pedometer to think you took more steps than you actually did. Write down how you did this.

____

____

____

____

ACTIVITY 2: DISCOVERING THE LIGHT SENSOR

Try to find where the light sensor is on the cube. You should see a label that says "light sensor".

Try to get the number on the LED Matrix down to 0.

Did you manage?

YES **NO**

How did you do this? ____

____

Now try to get the number on the LED Matrix as high as possible.

What was the highest number the sensor showed? _______________

What did you do to get this number? ____

____

What do you think the light sensor could be used for in real life?

____

____

ACTIVITY 2: DISCOVERING THE TEMPERATURE SENSOR

Try to find where the temperature sensor is on the cube. You should see a label that says "temperature sensor.

Try to get the number on the LED Matrix as low as possible.

What was the lowest number the sensor showed? ________________

What did you do to get this number? ____

____

Now try to get the number on the LED Matrix as high as possible.

What was the highest number the sensor showed? ________________

What did you do to get this number? ____

____

Try testing the temperature of your fingertips. Then, compare it to the temperature of your partner's fingertips. Was there a difference?

YES **NO**

If yes, why do you think the numbers were different? _____________________________

____

ACTIVITY 2: DISCOVERING GSR

The Galvanic Skin Response (or GSR) sensor measures how "conductive" your skin is. Your brain and body automatically make you sweat a little more when you are stressed, anxious or excited. The GSR sensor measures this change in "humidity" on your fingers.

Take a sharp, deep breath in. Does the GSR level go up or down?

UP **DOWN**

About how long did it take for the GSR reading to change? Was it instant or did you have to wait?

It took ____ seconds to change

With your partner, take turns asking each other difficult questions, or telling white lies. Then fill in the blanks below:

What was the highest number the sensor showed? ________________

What did you do to get this number? ____

____

What was the lowest number the sensor showed? ________________

What did you do to get this number? ____

____

Try tricking the GSR sensor. For example try to get the reading to stay the same when you are telling a white lie. Write down how you tried to trick the sensor and if it worked.

____

____

____

____

APPENDIX C: LIST OF THE MAGIC CUBES OUTREACH EVENTS CARRIED OUT DURING THIS PHD

This appendix comprises a complete list of outreach events with the Magic Cubes that were deployed both in classrooms and informal contexts throughout this PhD, beyond those reported in the empirical chapters of this thesis.

09/2019	**AI and Art Futures Symposium at the Barbican** Demonstrated the Magic Cubes to an audience of creative practitioners, museum and gallery staff and academics as part of a symposium on the future of AI and computing to creativity (audience of ~100)
04/2019	**Creative Informatics Studio, Edinburgh** Demonstrated the Magic Cubes to an audience of creative practitioners in Edinburgh (audience of ~30)
10/2018	**Science Museum Year of Engineering** Ran workshops over 2 days with the Magic Cubes at the Science Museum Year of Engineering to a wide audience of children and families; reached > 250 members of the public
10/2018	**EU Codeweek UK** Delivered an introductory tinkering and programming session to 8-10 year olds; reached ~30 children
01/2018	**Emirates Digital Celebration at Emirates Stadium** Engaged London teachers and educators with the Magic Cubes
11/2017	**Big Bang Launch at the Natural History Museum** Engaged educators Greater London with the Magic Cubes
10/2017	**Making Magic with the Magic Cubes (MozFest 2017)** Led a drop-in session, open to children and adults, to teach

	introductory programming with Arduino; ~30 people
08/2017	**Grenfell Tower Kids Summer Coding Camp** Organised and led programming and prototyping activities for children affected by the Grenfell fire
06/2017	**It's All Academic Festival** Engaged University of London alumni with the Magic Cubes research project
05/2017	**Bringing the Magic Cubes to special education schools** Organised educational sessions at two special education needs schools in Southern England (~20 students)
11/2016	**Hackney University Extension Coding Masterclass** Prepared and delivered a coding class to ~30 sixth form students
10/2016	**Hands-on Exploration of Issues with the IoT (MozFest, 2016)** Led a session to critically engage the public with IoT data privacy (~10 attendees)
09/2016	**Newnham Collegiate School Induction Day** Delivered a session on Magic Cubes and low-fidelity prototyping methods (~15 students)
06/2016	**Interaction Design and Children conference BBC day** Demo session to engage child-computer interaction researchers with the Magic Cubes
04/2016	**CHI 2016 ConnectUs demo** Demo session to engage HCI researchers with the Magic Cubes
04/2016	**Engineers Save Lives: Royal Institution Masterclass** Organized and led a 3-hour coding session for Year 9 students (~30 students)
11/2015	**Big Bang Fair** Facilitated programming activities with a wide range of students