Learning and cognition in the computing science classroom: a study on conceptual understanding for young learners

Anaclara Gerosa

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College of Science and Engineering
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Abstract

The main objective of this thesis was to investigate how children acquire and develop conceptual understanding of three fundamental computing concepts during preschool and the first year of primary education.

According to grounded cognition theory (Barsalou, 2020), we, as humans, create concepts by transforming our experience with sensory and motor information into mental simulations. In addition, these theories posit that scaffolding learning through action and concrete objects might have an impact on students' understanding.

A recent theoretical contribution specific to the field of computer science education, the EIFFEL model (Kallia and Cutts, 2022) was developed based on grounded cognition theory to support young children's conceptual understanding. The theoretical framework proposes a sequence of learning that scaffolds children from highly concrete, physical actions and objects towards increasingly abstract paths of abstraction that finalise in formal, symbolic representations and operations we can perform mentally.

With the increasing introduction of computing education in mandatory curricula worldwide for young children (Bocconi et al., 2016), it is essential that we, as academics, teachers and practitioners, have empirical, developmental and contextualised data that can account for children's conceptual understanding and how this changes through time.

This thesis comprises five phases of study: in phase 1, I conducted a systematic literature review of action-based and grounded activities in the last two decades, in order to identify relevant experiences in promoting children's understanding through a grounded cognition perspective.

In phase 2, I use design-based research to co-create with a group of teachers a set of activities that incorporate concreteness fading and object-action congruency as early computing activities, based on the theoretical contributions of the EIFFEL model to extend its theory into practice.

In phase 3, part A, I employed classroom ethnography to explore the intricacies of the application of the instruction sequence designed in the previous phase in two early childhood classrooms during 10 weeks. This phase of research allowed me to identify a set of behavioural and verbal indicators of conceptual understanding for young learners.

Phase 3, part B, I employed a microgenetic and quasi-experimental design in order to empirically test the intervention, using both quantitative and mixed-methods approaches with a special focus on rich longitudinal data across sessions. Last but not least, phase 3, part C of the study, explores teachers' perspectives and insights on the implementation through qualitative analysis of in-depth interviews.

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Declaration

I declare that all the work in this thesis was carried out by the author unless otherwise explicitly stated, under the supervision of Dr. Maria Kallia.

Chapter 1

Introduction

1.1 Computing science education

Computer science has become a mandatory subject across school curricula worldwide (Bocconi et al., 2016; Hubwieser et al., 2014; Oda et al., 2021; Webb et al., 2017). In fact, many countries around the world are beginning to introduce computing and computational thinking from an early age (Bati, 2022; Macrides et al., 2022; Yang et al., 2024), with research showing that children as young as three are able to grasp foundational aspects of computing through developmentally appropriate methods (Bers, 2020).

The arguments for introducing computing science to young children are well documented and reported in recent literature: while some authors point to the overwhelming use of computational devices in our everyday life and the need to be able to comprehend these at more than user level (Armoni and Gal-Ezer, 2014; Crick and Sentance, 2011; Webb et al., 2015; Wing, 2011), others argue there are economic benefits for countries in terms of creating skilled workers who are able to engage with complex technology and fuel innovation (Osín, 1998). Even so, for those who will not become computer scientists in the future, knowing and understanding the foundations of the discipline and acquiring practical tools such as programming has been suggested to have benefits in terms of their cognitive abilities (Liao and Bright, 1991; Scherer et al., 2021, 2019) as well as in regard to their self-efficacy in computing (Hasan, 2003; Moos and Azevedo, 2009). As such, there is agreement across academic and educational contexts that computing is an essential skill for current learners, and there are benefits to beginning the introduction of computing notions at an early age (Armoni and Gal-Ezer, 2014; Rich et al., 2019c).

However, despite this general agreement, the ways in which computing has been implemented in schools have varied greatly both in practice and in theory (Storte et al., 2019); for example, while some curricula are more focused on teaching broader skills related to computational thinking and approach it as a general problem-solving ability that is taught transversally across different fields of knowledge, others tend to focus more on its relation to programming and conceptual knowledge in computing (Bocconi et al., 2022).

Thus, despite considerable interest in the topic from both practitioners and researchers (Haseski et al., 2018), recent literature reviews point to a high degree of conceptual diversity in the field (Grover and Pea, 2013; Haseski et al., 2018; Lowe and Brophy, 2017). Taken together, these arguments suggest that, while the importance of computing is well established, the literature is less clear on basic curricular content and sequencing.

When examining relevant and highly cited antecedents for the introduction of computing for young children, this conceptual diversity described in the literature is also present. One of the most important pioneering works in early years computing was that conducted by Seymour Papert and his impactful work with LOGO (Papert, 1980). He proposed that computer programming not only could be brought to children but was also a beneficial activity in terms of supporting active learning. In terms of how conceptual knowledge is built, Papert aligned himself with Jean Piaget's (Piaget et al., 1980) constructivist ideas, emphasising the role of tinkering and action in this process. More recent work, such as that of Brennan and Resnick (2012), also highlights the role of conceptual knowledge; their influential framework on computing defined three areas of focus in the early years: computational concepts, computational practices, and computational perspectives. While computational practices and perspectives encompassed the actions and socio-emotional dispositions children must engage with during computer programming, computational *concepts* defined seven ideas young children would need to familiarise themselves with and learn. These comprised: sequences, loops, parallelism, events, conditionals, operators, and data (Brennan and Resnick, 2012).

However, there have been broader approaches to considering the conceptual knowledge that students need in their computing science learning. For example, in their K-12 framework (K–12 Computer Science Framework Steering Committee, 2016), the Association for Computing Machinery, Code.org, the Computer Science Teachers Association, Cyber Innovation Centre, and the United States' National Math and Science Initiative have established computing systems, networks, and the Internet, algorithms and programming, and the social impacts of computing as overarching concepts in the computing curriculum. Distinctively, Brennan and Resnick's concepts are specifically focused on programming (Brennan and Resnick, 2012).

In the United Kingdom, initiatives such as the Computing at School curriculum (Berry, 2013) define that students between 5 and 7 years of age should *"understand what algorithms are; how they are implemented as programs on digital devices and that programs execute by following precise and unambiguous instructions"* (Berry, 2013, p. 7). This approach emphasises for its younger students conceptual knowledge regarding algorithms, sequences, notions of input and output, data, debugging, and digital content, as well as practices such as searching and logical reasoning. This knowledge is expected to create the basis for understanding more complex notions later on, with students aged 7 to 11 focusing more deeply on programming structures such as sequencing, selection, repetition and variables, among others.

This conceptual diversity is not just limited to academic and research-oriented fields, but can also be found in education, where different educational systems have taken a wide range of routes in their paths towards the implementation of computer science in schools. In a recent review of implementations from thirty different countries, Bocconi et al. (2022) described that conceptual knowledge is an integral part of most curricula, but that there are substantial differences in their scope.

As shown above in my summary of some of the most cited curricular approaches, we can identify that a strong conceptual basis is an integral part of the discipline's building blocks. This makes sense, as creating and relating concepts is essential to the overall learning process (Novak, 2010).

Taking this into account, it is especially relevant to understand how young children develop conceptual knowledge in the context of computing education, which is the focus of this thesis. In the following section, I will expand on the significance of conceptual understanding for young children who are learning computing and its implications for practice.

1.2 Trajectories of conceptual understanding in computing

Concepts are one of the means through which we store and represent experience, and thus are central to all humans' cognitive development. Yeh and Barsalou (2006) defined a concept as "the accumulated information in memory abstracted for a category, where a category is a set of things in the world perceived as the same type of thing (for one of many possible reasons)" (Yeh and Barsalou, 2006, p. 352). As such, conceptual understanding can be understood as a process of abstraction of the most important characteristics or elements in a process that create a coherent description of it (Hurrell, 2021).

While this topic has a long trajectory within the field of science education (Brown and Hammer, 2009; diSessa, 2014; Love, 2015; Nersessian, 1989), the current literature suggests that children's conceptual understanding regarding early computing concepts has been underexplored.

Following the definitions of concepts cited above, it follows that discussing ideas such as sequences, loops and conditions necessarily means talking about abstract representations that create regularities in meaning. How do we, as humans, create those regularities? Developmental evidence has consistently shown that children typically begin their conceptual development by learning concrete concepts before progressing to abstract concepts as they grow and develop cognitively (Caramelli et al., 2004; Villani et al., 2022).

In addition to the conceptual diversity that is often found in different computing curricula, the literature points to a wide variety of pedagogical approaches to teaching computing, especially in the early years. When focusing specifically on early years education, we can identify studies focusing on the use of robots, block-based virtual programming, and unplugged materials (Grover and Pea, 2013; Min et al., 2020; Yu and Roque, 2019; Zhang and Nouri, 2019).

Thus, while there are several pedagogical and technical tools to teach young children computing and programming, there seems to be less clarity regarding which concepts to teach and when and at what stages these concepts should be taught in order to make the most out of their cognitive capabilities as well as promote their overall development.

Thus far, few studies have focused on empirically describing learning trajectories for students. A few exceptions to this are to be highlighted: previous conceptual work by Kallia and Cutts (2022) describes a theoretical trajectory for conceptual understanding in the early years of computing education based on the contributions of grounded cognition theory for understanding how children develop and consolidate their conceptual understanding through the use of concrete objects at first and then incorporating increasingly abstract notions. This study contributes directly to this line of work by both expanding this model and empirically evaluating the existing trajectories.

In a set of studies, Rich et al. (2017) created a set of learning trajectories based on previous research for the concepts of sequences, repetitions, conditionals, debugging (Rich et al., 2019a), decomposition (Rich et al., 2018) and variables (Rich et al., 2022). However, they were not successful in making their learning trajectories developmental, given that most of the studies they examined were conceived as introductory yet offered to students of widely different age ranges. As such, their findings highlight the need for developmentally informed learning trajectories of computing concepts that are based on research and explore young children's path towards conceptual understanding.

Throughout this thesis, I sought to bridge this gap in research by firstly, targeting conceptual knowledge in computing and focusing on fundamental concepts such as sequences, loops and repetition, which are named as relevant in most of the reviews on the topic targeting young children (Bers et al., 2022b). Secondly, conducting a developmental study, meaning that this thesis will focus specifically on describing how children and their conceptual understanding of computing notions change through time. In order to achieve this, I needed to implement research designs and methodologies that allowed me to follow children's trajectories through time from a situated perspective. Thus, to accomplish this, I implemented a microgenetic design and ethnographic research methodology, as the microgenetic approach allows the repeated observation of developmental changes throughout children's learning process (Chinn and Sherin, 2014; Puche-Navarro and Ossa, 2024; Siegler, 2006), and ethnography allows for the possibility of rich and highly situated insights into participants' processes (Nixon and Odoyo, 2020; Pole and Morrison, 2003). Albeit highly extended in the social sciences and humanities, these methodological strategies are less often utilised in computing education research. As such, this thesis provides practical and methodological insights by applying these methodologies in the context of early computing education.

Moreover, exploring students' conceptual understanding trajectories is relevant in order to identify possible points where students struggle and create targeted interventions in order to mitigate this. Previous research has highlighted that, while young children have shown to be able to grasp computing concepts, many of them still struggle to learn the foundations and are impacted in their learning later on. As their cognitive abilities are still developing, many might need scaffolding to support their learning. A recent review by Boude Figueredo et al. (2025) from 84 studies in computing targeting children from ages 3 to 6, showed that despite design efforts, several of their examined studies needed to adapt either their pedagogy or tools for younger children. Similarly, a randomised control trial study using Scratch Jr, a block-based visual programming language designed for early ages, in children aged 7 to 8 (Yang et al., 2025) found that while their coding proficiency did improve, abstraction and computational thinking were not affected, suggesting that while procedural skills might be gained, conventional curricula might not be as efficient in fostering a deeper understanding. Taking this into account, it becomes specifically relevant to focus on young children's conceptual understanding, an area that has been highlighted as important in the discipline but has thus far seen more development in adult learners and teacher education (Grover, 2021).

Regarding this, it is an additional challenge that has been reported in the literature that often teachers providing computing lessons to younger children are not specialist computer science teachers but generalist teachers who often struggle themselves with low self-efficacy in computing and a need to develop their content knowledge in computing (Menekse, 2015; Yadav et al., 2015). In this sense, a review by Waite (2017) identified several studies highlighting the need for mentoring opportunities for teachers for both content and pedagogical knowledge. This thesis sought to work alongside a group of generalist teachers in order to construct a realistic and feasible intervention that meets young children's cognitive abilities and is implementable for teachers. In order to address this, this thesis will focus not only on children's conceptual understanding trajectories but also on capturing teachers' experiences in relation to students' understanding.

In this sense, it is necessary to think of teaching practices in computing education that are easy to implement and developmentally appropriate to the early childhood and first years of primary school context. Furthermore, in the preschool and early primary context, one of the main challenges consists of how to evaluate students' conceptual understanding, considering most children are in the process of acquiring and perfecting their reading and writing skills, and writing-based strategies used for older children cannot be implemented (Kalman, 2011). For younger children, verbal and behavioural indicators of conceptual understanding in computing have not yet been identified. Thus, identifying indicators of conceptual understanding in this situated context was a prerequisite for exploring their trajectories.

In order to theoretically support the design of the activities, I used grounded cognition as one of the principal theories guiding this research (Barsalou, 2003, 2010; Barsalou et al., 2008). In the following section, I will introduce the main ideas behind grounded cognition theory and argue why it is a relevant theory in the process of thinking about young children's conceptual understanding and their trajectories during learning.

1.3 Grounded cognition and computing

Grounded cognition is a theory of cognition that stresses the importance of the body, environmental restraints and action in the ways we, as humans, create mental representations of the world around us (Barsalou et al., 2008). According to grounded cognition, the abstract mental representations that we can conjure during adulthood are actually grounded in experience, meaning our actions in a specific, situated physical body and environment. This notion is supported by empirical evidence of motor activation in the brain when subjects are thinking of specific concepts, pointing to a functional link between conceptual analysis and motor abilities (Barsalou, 2015).

In light of this, some authors have pointed out that principles from grounded cognition might be applicable to scaffold students' learning (Shapiro and Stolz, 2019). In fact, some activities that have already been reported in the literature to be successful as tasks for young children to do to learn computing science during their early years can be theoretically associated with the tenets of grounded cognition theory (Trory, 2016; Trory et al., 2018). These are not obscure practices, but practices early childhood and primary educators who teach computing and other disciplines might frequently use, such as the use of unplugged, tangible materials (Caeli and Yadav, 2020), or strategies such as starting from concrete notions and then moving on to more abstract ones, often referred to as concreteness fading (Trory, 2016; Trory et al., 2018).

In line with this body of evidence, Kallia and Cutts (2022) developed the EIFFEL (Enacted Instrumented Formal Framework for Early Learning in Computing) as a theory-driven pedagogical framework designed to use the principles of grounded cognition theory to create a sequence of instruction that scaffolds young children's conceptual understanding in computing.

The EIFFEL model puts action at the centre of learning: following Barsalou's (Barsalou, 2010; Barsalou et al., 2008) notions, it considers action and cognition as interrelated (Kallia and Cutts, 2022). Moreover, the model proposes three phases of action that students go through in the process of improving their conceptual understanding in computing: the enacted phase, in which children use their body or physical actions to represent a given concept, thus supporting their conceptualisation; the instrumented phase, in which children use actions that include using their hands to control symbolic instructions or manipulate an object, and lastly formal, in which a formalised language such as code is used to represent and manipulate objects (Kallia and Cutts, 2022).

Thus far, while the EIFFEL model is a useful conceptual model to structure students' learning, there have not been instructional materials and lesson plans designed to follow the specifications of the model. Thus, there is a need to complement the conceptual model with an instructional model that consists of activities tailored to its ideas. Part of the work of this thesis consisted of the design of teaching materials based on this model in order to build on the previous theoretical work, as well as empirically assessing its effectiveness. Moreover, this thesis constitutes the first empirical implementation of the EIFFEL model.

In addition, the present thesis aimed to provide evidence on young children's conceptual development in the setting in which it occurs (early years computing classrooms) with their teachers in order to contribute to our current understanding of the development of foundational aspects of computing education that will later impact the ecology of the computing science classroom at multiple levels, both through teacher's content knowledge and student's conceptual understanding.

More importantly, the study sought to have a developmental perspective through the use of methodologies that are focused on capturing change through time (Overton et al., 2015). This is implemented in my empirical analysis through a mixed methods approach that combines both quantitative and qualitative data in order to create a comprehensive picture of the learning environment and allow for the observation and analysis of change. As mentioned, the methods used in this thesis are ethnography (Pole and Morrison, 2003), a qualitative approach that allows for the analysis of a highly complex and multi-determined environment such as the computing classroom, and the microgenetic method (Chinn and Sherin, 2014), which allows for the description of children's conceptual change throughout the weeks of implementation. In order to do this, an intervention based on the EIFFEL model and co-designed with teachers was implemented over 10 weeks at a middle-income private school in Montevideo, Uruguay. A total of 29 children between 5 and 7 years of age and 2 teachers across two classes: one in the final year of preschool and one in the first grade of primary education; participated in the quasi-experimental section of the study.

Next, I present my research statement and questions, as well as provide context on the structure of this thesis.

1.4 Research statement

A pedagogical and instructional framework for teaching computing based on Grounded Cognition will improve young children's (5–7 years old) acquisition of basic CS concepts (sequences, conditionals and loops) and their computational thinking scores compared to a passive control group.

1.5 Research questions

The main research questions that this thesis aims to address are the following:

a) What kind of approaches related to grounded cognition can we identify in current practices for teaching early years computer science?

b) How can an instructional model based on grounded cognition be designed for its implementation in early years computing classrooms?

c) What behavioural indicators are there of conceptual understanding in early years computing classrooms?

d) Does an intervention based on the EIFFEL model scaffold children's conceptual understanding of computing concepts?

1.6 Publications

This section summarises the academic publications that are a result of the process of conducting this thesis.

- A Systematic Literature Review on Physical and Action-Based Activities in Computing Education for Early Years and Primary (Gerosa et al., 2023).

  This paper was presented at the 2023 WiPSCE Conference on Primary and Secondary Computing Education Research, held in Cambridge, UK.

- Enhancing conceptual understanding in early years of Computing education (Gerosa and Kallia, 2025)

  This paper was presented at the 2025 Computing Education Practice conference held in Durham, UK.

1.7 Thesis structure

This thesis is structured as follows: firstly, this introduction chapter aims to provide an overview of the research problems and contributions of this thesis. Chapter 2 comprises the literature background chapter, which provides a detailed overview of the main constructs that support this research. In this section, I explore the landscape of computing education with a specific focus on conceptual understanding and the ways in which conceptual knowledge is embedded in the teaching and learning processes in computing. In addition, I examine conceptual development from a broader context, bringing evidence from cognitive science and psychology, to provide context as to how these fields have approached the study of conceptual development, including major philosophical and pedagogical stances as to the nature of learning and development itself.

Next, I present the fundamental tenets of grounded cognition and its implications for both development and learning of computer science, with a focus on conceptual development in the context of computing education for young children, providing empirical examples in order to provide an overview of previous relevant evidence. Additionally, I present the systemic and socio-cultural perspective and its theoretical and methodological implications for this research, as well as the relevant instructional implications of this literature in the context of computing science education.

The methodology (chapter 3) aims to provide a detailed description of both the methods utilised throughout this research as well as its ontological and epistemological framework in order to provide readers with the rationale behind each methodological decision in light of the research questions examined. This thesis is structured in five phases of study, and both the methodology and results sections of this document are divided into each of these phases for clarity.

In phase 1, I conducted a systematic literature review of grounded and action-based approaches in order to identify previous relevant research that used tools related to grounded cognition theory in order to promote young children's learning of computing.

In phase 2, design-based research and participatory design techniques were used to co-create a set of feasible, developmentally appropriate computing activities based on the EIFFEL (Kallia and Cutts, 2022) model for computing education, for young children, along with participating teachers.

In phase 3-A, I used ethnography to explore the computing science classroom setting and particularly behavioural indicators of conceptual understanding, in two preschool classes, one involving 5-year-old children and one involving 6-year-old children in a primary classroom.

Phase 3-B involved the empirical evaluation of the application of the activities designed in the context of the EIFFEL model and took a developmental perspective by using a microgenetic design and analysis.

Finally, phase 3-C focuses on the qualitative exploration of teachers' perspectives regarding the EIFFEL model as well as its impact on their technological and pedagogical content knowledge.

The structure that organises the present thesis is depicted below in Figure 1.1

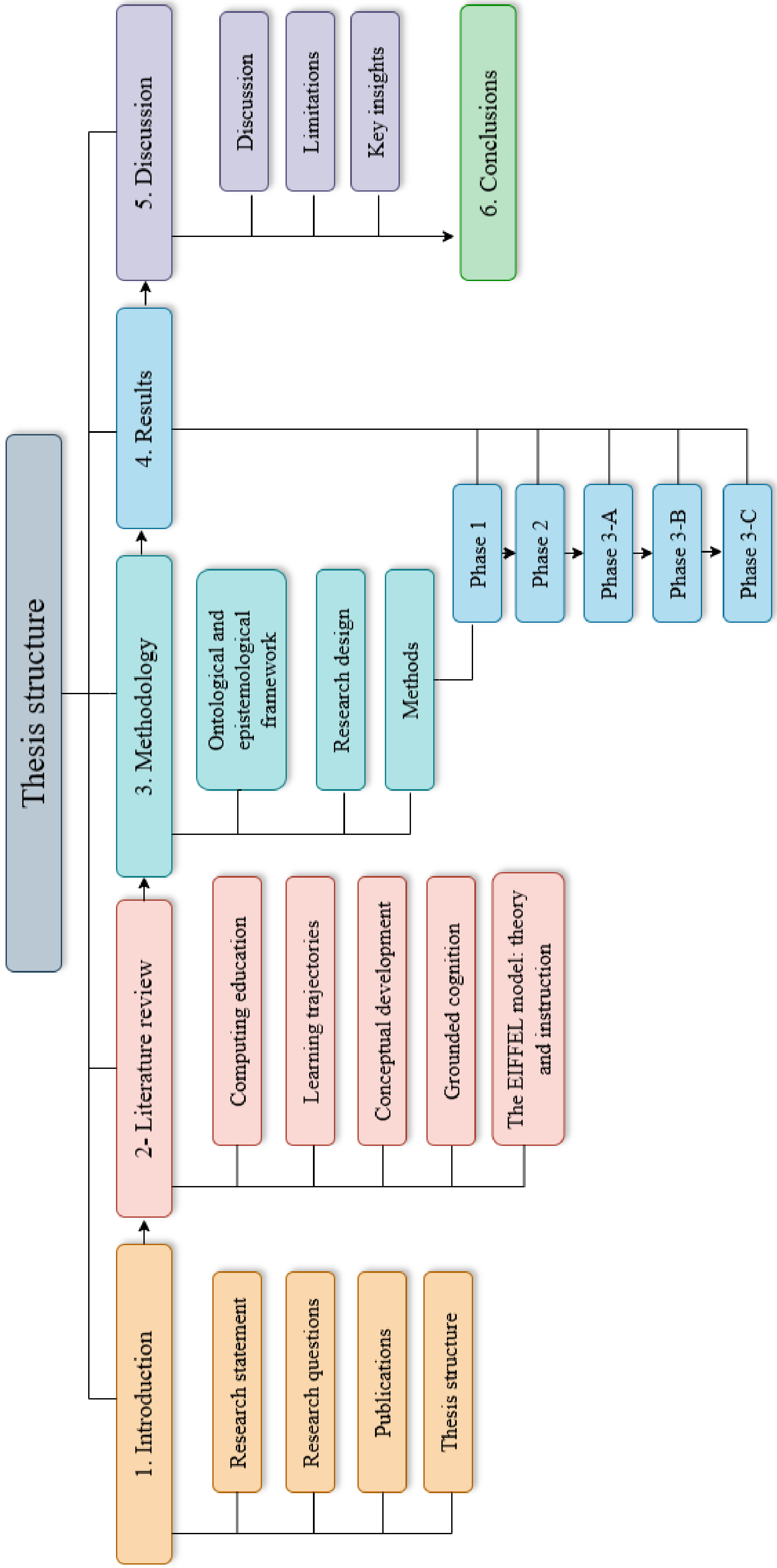


Figure 1.1: Thesis structure

Chapter 2

Literature review

The aim of this chapter is to provide an overview of the theoretical foundations supporting this thesis. In order to do this, I will describe the computing education landscape and its relation to conceptual knowledge in computing, as well as describe further the contributions of grounded cognition theory to early years computing education. In addition, I will contextualise this research within systemic and socio-cultural perspectives of learning. Finally, I will focus on the instructional aspects of early years computing.

2.1 Computing education: brief history, current landscapes and empirical approaches

Computer science emerged as an academic discipline in parallel to major developments in technology during the 20th century (Denning, 2005). The field has been defined as *"the systematic study of algorithmic processes that describe and transform information: their theory, analysis, design, efficiency, implementation and application*"(Denning et al., 1989). Pioneers of the field, such as Alan Turing (Turing, 1936), would establish a blueprint for modern computers as general-purpose machines.

During the last five decades, computing has expanded into several disciplines and subdisciplines, which include engineering, human-computer interaction, and software design, among others. As computer science curricula started to proliferate at the university level, so did the notion that computer science would be useful beyond the discipline. It was not long before scientists began using computers as a metaphor for human thinking: parallels between computers and the mind, and the notion that computers could be considered aids for thinking, for example, go back to the 1960's (Pfeiffer, 1962).

In the 1980's, Seymour Papert and colleagues at the Massachusetts Institute of Technology introduced their influential work on LOGO (Papert, 1980), a programming language aimed at teaching children and beginners the fundamentals of programming in a playful way. Papert had studied under Jean Piaget, a recognised cognitive psychologist, who laid the groundwork of constructivist theories of learning (Piaget et al., 1952) and pioneered a new way of thinking about cognitive development during childhood. Papert referred to his ideas behind LOGO as "constructionist" (Papert, 1980), as students are able to construct through programming aspects of the real world, and create understanding in the process (Papert and Harel, 1991). Papert's influence and ideas regarding bringing computing to support children's thinking processes consolidated the notion that it could benefit and be taught to everyone.

During the early 2000s, Papert's ideas saw a resurgence (Lodi and Martini, 2021), not only in computing but in neighbouring terms such as computational thinking; an umbrella term emphasising the cognitive processes behind computer science with a focus on goal-oriented behaviour such as problem solving (Wing, 2006). In particular, Jeanette Wing wrote an influential opinion article titled "Computational thinking" in the March 2006 Communications of the Association for Computing Machinery (Grover and Pea, 2013; Wing, 2006). This communication was successful in sparking academic interest in computational thinking and established a research agenda that would greatly impact the landscape of computing education (Grover and Pea, 2013). Wing referred to computational thinking as something that: *"is a fundamental skill for everyone, not just for computer scientists. To reading, writing and arithmetic, we should add computational thinking to every child's analytical ability.* (Wing, 2006, p.33).

While Wing's definition has been previously criticised as being too broad (Selby and Woollard, 2013), its emphasis on thinking processes could lead us to conceptualise computational thinking as the underlying cognitive processes necessary for programming (Li et al., 2020; Selby and Woollard, 2013).

In the last few decades, we have seen the inclusion of computing and computational thinking in mandatory school curricula all over the world. However, it is worth noting that while curricula might refer to computational thinking, the term often includes aspects of robotics, computer science and programming (Kakavas and Ugolini, 2019). A review of educational policies in Europe reflected that most nations were incorporating computing into their mandatory curriculum from an early age (Bocconi et al., 2016). Moreover, in 2021, computational thinking was incorporated into the mathematical module of the standardised PISA assessment (Lorenceau et al., 2019).

In the United Kingdom, the group "Computing at School" (CAS), composed of teachers and academics, formed in 2008 to promote computing at schools (Crick and Sentance, 2011). In 2010, Scotland began implementing its "Curriculum for Excellence" which establishes computing science as a subject for ages 3 to 18 and specifically notes the difference between the teaching of computing science and information and communication technologies (ICT) (Kidner, 2013). Computer science has been a subject in Scottish educational tradition for several years, and the country has preserved teacher training in the subject (Brown et al., 2014) which put it in an advantageous place when compared to the rest of the UK, which had focused on ICT skills and digital literacy since the 1990s and 2000s. In 2012, England reviewed its national curriculum to include computing science as well, promoting it as a compulsory subject from the age of 5.

Despite the curricular move, the lack of teacher training and professional development opportunities has caused challenges in its implementation (Fowler and Vegas, 2021). Issues of a similar nature have been recently reported by researchers in the United States, where opportunities for teacher training, time management and access to resources have been identified as key issues (Wang et al., 2016).

Curricular reform has also been reported in Asia, as stated in the work of So and collaborators (So et al., 2020), in which the authors describe that Hong Kong and China, South Korea and Taiwan have recently introduced curricular changes with these aims.

In Latin America, Argentina (CFE, 2018), Mexico (Cardenas Peralta, 2018), and Chile (Uscanga et al., 2019) have all included computing into their mandatory curricula.

In Uruguay, efforts to introduce computing to compulsory education from an early stage are coordinated by the national administration of education (ANEP, by its Spanish acronym) and Ceibal, a government agency dedicated to the intersection between education and computing, technology and digital citizenship (Koleszar et al., 2021). In 2017, Ceibal launched its computational thinking programme, which reaches over 30,000 primary education children (Urruticoechea et al., 2021). The programme consists of a joint collaboration between classroom teachers and remote specialised teachers in the instructional design of computational thinking and computer science activities for children between 8 and 12 years of age. The participation of Ceibal in formal education has been increasing steadily since its creation in 2007 with the one laptop per child programme (Vaillant, 2013) and now offers not only technological solutions but also pedagogical support and professional development opportunities for teachers interested in computing and technology. Recently, the Uruguayan government has announced changes to the educational curricula, which mandate that compulsory education will now target (among other subjects) computational thinking, digital citizenship and computing science (Administración Nacional de Educación Pública (ANEP), 2022).

I have established a general consensus around the world on the value of computer science knowledge for children and adolescents, not only to become citizens of an increasingly technology-fueled world but to experience opportunities for abstraction, problem-solving and algorithmic thinking (Bers, 2017). I will now focus on a central aspect of this thesis: conceptual knowledge.

Conceptual knowledge has been a central aspect of most early computing curricula. However, differences in the selection of relevant concepts included can be detected when analysing the literature: for example, one of the most cited frameworks for early computing, such as that proposed by Brennan and Resnick (2012), establishes sequences, loops, events, parallelisms, conditionals, operators and data as relevant concepts in computational thinking. Similarly, Bers

(2021)'s powerful ideas in computing include algorithms, modularity, control structures, representation, hardware/software, the design process and debugging.

Thus, while curricular reform is happening around the world, the question of which content knowledge to prioritise at which stage and its intersection with developmental trajectories and processes arises. What concepts and processes in computing teachers should focus on is not a closed discussion yet for academia or public policy.

Another layer of complexity is given in the relation between the content that is being taught and the available tools teachers have to teach with. In computing education, the multiplicity of tools and devices designed with the purpose of introducing fundamental concepts to early learners is vast (Yu and Roque, 2019). For example, for children attending primary school several applications and graphical interfaces have been developed and promoted to introduce programming (Bati, 2022), these come with a wide spectrum of both opportunities and constraints and include (but are not limited to) virtual interfaces such as block-based programming languages, tangible interfaces such as robots and physical computing tools and hybrid options (for comprehensive review on the variability of these tools see: Bakala et al. (2021); Yu and Roque (2019)). Evidence from studies on children has shown that both Scratch and Scratch Jr. are motivating tools which have allowed children to learn basic programming (Montiel and Gomez-Zermeño, 2021; Zhang and Nouri, 2019). Despite these promising results, studies show some children have difficulties with block-based programming (Grover and Basu, 2017; Swidan and Hermans, 2017) From a pedagogical perspective, research on the learning trajectories of specific fundamental computer science concepts remains scarce (Rich et al., 2017).

Examining instructional practices, it can be observed that these often begin with programming tasks which require the instrumentation and integration of several concepts. For example, Ching et al. (2018) pointed out in their review that most apps and websites for early childhood (beginners) function under the premise of sequencing movement of a given character through code elements signalling directions (forward, backwards, left, right and turns) and most frequently address the concepts of sequence and looping. Similarly, the computational toys, robotics toolkits and other tangible elements examined (Ioannou and Makridou, 2018; Yu and Roque, 2019), which were targeted to this age range, follow a similar logic of movement and discrete sequencing. When children begin their learning of computer science through programming and robotics, they are required to have a fairly high level of abstraction (Mirolo et al., 2022; Wong et al., 2024): they must create mental models of the structure of programs, understand sequential and cause and effect relationships, comprehend conditionals, and understand the underlying rules to manipulate the information. Empirical research has shown that some children find this process more challenging than others. For example, a case study by Fessakis et al. (2013) showed that while most of the kindergarten children observed during digital programming activities solved problems by way of trial and error, others managed to plan their solutions, which points to a higher level of understanding.

Given the arguments presented above, it can be observed that the complexity of the computing education field lies in its richness: there is a multiplicity of concepts to teach as well as a wide variety of tools to teach them with. Moreover, as computing education is included in curricula at increasingly earlier ages, more research must be conducted on young children's understanding of these notions, what can be done to scaffold their learning and what their learning trajectories look like at an early age. These are elements I attempt to tackle throughout this thesis. In the following section, I will focus on the notion of learning trajectories and why it is relevant to have empirical information from young children. Moreover, this thesis focuses on a central aspect of learning computing: children's conceptual understanding of fundamental computing notions.

2.2 A need for learning trajectories:

Learning trajectories are defined as the path children's thinking and learning take in a domain through a set of tasks designed to support those mental processes through a developmental progression of thinking at different levels of complexity (Clements and Sarama, 2012; Ellis et al., 2014; Sztajn et al., 2012)

This study seeks to take a developmental approach to computing education in the early years (Lerner, 2012). As such, describing students' change through time is a key aspect of this approach. Thus far, very few studies have focused on empirically describing students' learning trajectories for computing concepts.

In 2017, Rich et al. (2017) examined the computing education research in order to create empirically supported learning trajectories for sequences, repetitions and conditionals, an enterprise that would later be followed by debugging (Rich et al., 2019a), decomposition (Rich et al., 2018), and variables (Rich et al., 2022). The authors based their work on a foundational question for education research, which seeks to answer which topics, and at what level, should be taught at different grades of formal education. However, as per their report, one of the main challenges they found when examining computing education research was that most of the examined studies (regardless of grade level) were targeted at novice learners. Thus, the same concept could be taught at the same level at wildly different ages. It is not hard to see why this might be a problem: while students of different ages might both be novice learners of computer science, their perceptual, cognitive and affective developmental stages could be extremely different. As such, a field that wishes to harness the strengths of children's cognitive capabilities at a given point to facilitate their learning is in need of developmental research approaches that aim to empirically describe children's learning process. This is not, however, a simple task: most intervention studies for young learners have often utilised a pre-test and post-test approach (Lye and Koh, 2014; Yu and Roque, 2019) that are useful for testing the overall effectiveness of the interventions but lack the repeated measures to properly describe gradual change.

Previous studies focusing on programming activities using floor robots (Strawhacker and Bers, 2019) used a cohort approach in order to examine young children's abilities. Thus, they examined children in kindergarten (5 years of age), first (6) and second (7) year of primary education. Through this approach, they were able to show that younger children committed more errors in their robot-based problem-solving task than older children. However, it is possible that a 1 year difference is too broad to understand the rich learning processes happening during early stages. Moreover, most early childhood and primary teachers would probably agree on the fact that children's learning does not necessarily follow a linear trend. Throughout both development and learning processes, there are qualitative jumps, slight setbacks and differing speeds at which each goal is achieved. This is not just an anecdotal observation: microgenetic research has provided compelling evidence that these processes exhibit complex, dynamic patterns characterised by fluctuations and variability over short periods of time. Microgenetic methods (Siegler, 2006) could thus partially bridge the gap pointed by Rich et al. (2017) through allowing for several observations through time and detailed descriptive analyses of change. For example, Siegler and Crowley (1991) demonstrated that children's strategy use in problem solving shifts frequently before stabilising, indicating non-linear developmental pathways.

In their review, Rich et al. (2017) point to the fact that they were unable to link children's ages to learning goals, which is a highly important aspect for teachers, especially when tailoring educational goals for their students. Moreover, they point to most studies focusing on single learning goals without the possibility of establishing links in the relationship between different learning levels. Thus, further research is needed in order to understand not just what children can learn at a given point/proficiency level, but also how the knowledge they build leads to more complex knowledge and how to scaffold those constructions. Finally, while learning goals based on research are effective in establishing what children are expected to do, they do not necessarily reflect what children actually do. As such, further empirical research is required in order to assess whether the established goals align with children's empirical trajectory, an aspect that will be covered in this thesis.

However, before I focus on how to study young learners' trajectories in their understanding of computing concepts, an even more elemental question must be tackled: What are concepts and how do we develop them?, this is the guiding question for the following section.

2.3 How do we develop concepts? Theories of conceptual understanding

What are concepts? Pines (1985, p.108) defined a concept as "packages of meaning that capture regularities", establishing "patterns or relationships between objects and events". Similarly, Novak and Cañas (2006, p.3) defined concepts as "a perceived regularity in events or objects, or records of events or objects, designated by a label" (e.g., a word or symbol). Concepts play a central role in children's cognition as they are means of representing and storing experience. Yeh and Barsalou (2006) defined a concept as "the accumulated information in memory abstracted for a category, where a category is a set of things in the world perceived as the same type of thing (for one of many possible reasons)." Yeh and Barsalou (2006, p.352).

An important theoretical distinction in this thesis consists of the differences between conceptual acquisition, conceptual change and conceptual understanding. I will refer to *conceptual acquisition* as the primary process through which individuals internalise and learn new notions. Sloutsky (2015) referred to the process of conceptual acquisition as composed of three main processes: first, forming categories through the process of abstraction, that is, identifying commonalities, second, lexicalising this process by applying the correct word to the correct category, and thirdly, using words to construct knowledge about the world by inferring properties within similar categories (for example, assuming if humans (single case) can feel, then all living things (category) are able to feel as well).

Conceptual change refers to the dynamic process that happens when children transition between different forms of a concept (Sloutsky, 2015). As we develop, our idea behind a given concept might start as naive, but through development, experience, and learning we tend to create increasingly sophisticated notions. In this sense, conceptual change is the product not only of coming into contact with novel information or situations but also of this new information's interactions with students' previous ideas and notions. Thinking about these processes in terms of conceptual change allows us not only to consider new concepts but also how an old concept might radically change its significance in light of new information Lehrer and Schauble (2015). Different theoretical approaches of conceptual change have had diverging views on the nature of this process, which will be revised in this section of the thesis.

I will reserve the term *conceptual understanding* to refer to the deeper process of both using concepts proficiently and being able to explain the underlying connections and relations between concepts (National Research Council, Committee on Developments in the Science of Learning, 2000). Some authors have related conceptual understanding to learning that is meaningful (Mills, 2016) and necessary in order to coordinate different items of related knowledge (Sands, 2014). In this sense, identifying when and how conceptual understanding happens is a central aspect of education (Biesta, 2009; Gabel, 2003; Konicek-Moran and Keeley, 2015). Moreover, (Sands, 2014) argued that the understanding of concepts is highly sensitive to contextual factors: concepts are not isolated notions but connected categories that contribute to the way we make sense of a multiplicity of pieces of knowledge. As such, one of the objectives of this thesis is to be able to identify young children's process of conceptual understanding as they engage with computing concepts.

Lastly, if a longitudinal perspective is to be considered, all of these processes (acquisition, change and understanding) can be referred to as the broader process of *conceptual development*. When talking about conceptual development, we situate the process in a typically incremental trajectory that tends to relate to children's increased cognitive capacities as they mature. Table 2.3 presents a summary of the conceptual distinction mentioned above.

Table 2.1:Conceptual learning: conceptual distinctions

Concept	**Description**
Conceptual Acquisition	The primary process through which individuals internalise and learn new notions. Consists of forming new categories, linking these categories to words and applying them correctly.
Conceptual Change	The dynamic process that happens when children transition between different forms of a concept. It relates not just to the new knowledge acquired but also to children's previous notions.
Conceptual Understanding	The process through which children demonstrate meaningful and situated knowledge of the concept. Is characterised by the ability to explain the concept, apply it appropriately in novel situations, and relate it coherently to other relevant concepts.
Conceptual Development	Relates to children's incremental capacities as they grow and learn and encompasses the processes of acquisition, change and understanding.

As presented above, these processes are an integral part of educating children, and how we acquire conceptual understanding has been a preoccupation of the learning sciences since their inception (National Research Council, Committee on Developments in the Science of Learning, 2000; Sawyer, 2005). Several philosophical and epistemological theories have tried to provide an answer as to how this process of acquiring, changing and understanding concepts happens. In order to analyse these theories, I will start by locating them on a spectrum that goes from nativism to empiricism. Nativist views correspond to those that understand concepts as innate or "hardcoded" into human nature, pointing to the existence of pre-built mental structures that promote development (Griffiths et al., 2002; Spelke et al., 2009, 1998).

On the opposite side of this spectrum, there is empiricism, which considers that learning and development happen through the accumulation of sensory experiences (Matthews, 2013). While this has been a long-standing and ongoing debate in philosophy that was then inherited by the learning sciences, the aim of this section is to provide an overview and contrast and compare both classic and contemporary theories in order to understand how we have thought about and valued conceptual knowledge throughout history.

Perhaps the most influential and well-known classic academic enterprise in understanding not just conceptual understanding but knowledge-building as a whole can be found in Swiss biologist Jean Piaget (Piaget, 1967, 1977). Piaget contributed to the understanding of conceptual change and understanding by empirically testing his hypothesis that children gradually change the way they think and construct knowledge throughout their development. In his view, the nativism-empiricism debate was to be overcome by emphasising the role actions have in knowledge (Piaget et al., 1980), while he did not reject the existence of simple, innate structures such as the babies' reflexes, he emphasised that it was in the joint-action of innate structure and experience that knowledge truly occurred. According to Piaget, new ideas stem from previous constructions (what he called schemas of thought) diSessa (2014), and concepts are shaped through a process which involves the subject actively exploring and interacting with its environment.

In addition, Piaget constitutes an important antecedent in the idea that concrete operations precede proper abstraction (Piaget and Inhelder, 2008) by consolidating a structuralist approach to child development in which this process is conceived as sequential stages that go from highly a purely practical intelligence (which he defined sensory-motor stage and encompasses roughly from birth to 2 years of age) based on physical actions, to a highly abstract and complex intelligence which allows us to use logic and deductive thinking (reached, according to Piaget, approximately by adolescence) (Piaget et al., 1952; Piaget and Inhelder, 2008). Piaget himself had early interests in biology and specifically zoology, which greatly influenced his later focus on scientific thinking. As such, his writings have been highly influential in STEM disciplines (Science, Technology, Engineering and Mathematics) as well as computing (Gluga et al., 2013; Lister, 2020; Zhang, 2022; Zipitría, 2018).

While Piaget himself did not live in a time when computing targeted specifically to young children was a part of mandatory schooling, if I follow his logic, it can be deduced that the abstract nature of computing concepts would present a challenge for young children. According to Piaget (Piaget et al., 1980), children in the intuitive pre-operational stage of development (approximately 4 to 7 years of age) have not yet developed the mental schema necessary to grasp highly abstract notions.

Several contemporary authors in computing education and adjacent fields maintain Piagetian and neo-Piagetian views. For example, Zipitría (2018) used a Piagetian model to theorise changes in abstraction in the context of teaching computational thinking to secondary-level students, which led her to design strategies to scaffold their abstract thought through metacognitive strategies and self-reflection. While working with children aged 6 to 8, Zhan et al. (2022) used a neo-Piagetian model to analyse their results in using unplugged activities to scaffold young students in a computational thinking intervention, obtaining positive results for their treatment group but finding evidence that children's egocentric stance presented challenges in taking a third-party perspective in order to solve computing problems. A recent study by Cerovac and Keane (2025) aimed to test the relation between children's performance in a school-based technology curriculum and Piaget's developmental stages, verifying that older children outperformed younger children in most tasks.

Piaget's influence in computing education can not be denied, not just because of his impact in the cognitive and learning sciences but also through his mentorship of Seymour Papert (Caeli and Yadav, 2020; White, 1985), who based his constructionist perspective in Piaget's constructivist ideas about learning and whose work set the basis for a rich field of research based on hands-on, action-based computing encompassing unplugged activities, physical computing and early childhood robotics. Papert's views built on Piaget's work through emphasising the role of external artefacts in knowledge building through the creation of tangible models and simulations that strengthen children's understanding of concepts and processes (Papert, 1980; Papert and Harel, 1991; White, 1985). Of course, Papert's biggest break from Piaget comes from his hesitation in adhering to the strict sequence of cognitive development defined by his mentor. When asked directly about it in an interview conducted by Barbara White in 1985, Papert gave the following response:

> **White:** What about stage theory — the claim that these ideas are developed in a definite order?
> **Papert:** Well, I don't believe that. There is no doubt that there is a fair amount of evidence in Piaget's work suggesting that they come about in pretty much the same order. The question is, could that order be changed? Personally, I think it can, by making radical changes in the early environments of children (White, 1985).

These "radical changes" he pointed out would be the inclusion of computers in young children's environments. According to Papert, computers presented children with an opportunity to turn very abstract, typically formal operations into concrete ones. Thus, he considered Piaget's views on children's ability to understand abstract notions to be somewhat more flexible.

More recent theoretical approaches to conceptual acquisition have turned closer to the spectrum of nativist perspectives. For example, authors such as Spelke et al. (1998) propose human beings have a set of "core knowledges" about objects and the physical world, numbers, space, geometry and social relations that are the building-blocks of conceptual understanding in different settings. This set of core knowledges allow babies to make sense of the world at an early stage. Although core knowledge provides a solid basis of early "intuitions" about the world, these could also give rise to misconceptions when contrasted with more complex evidence. Conceptual understanding is, from this perspective, the process through which children's core knowledge interacts with experience. Evidence on this line of research has focused on testing the limits of babies' understanding of the world: for example, Baillargeon (1999) contradicted Piaget's classical stances on object permanence by showing that children as young as three months of age had expectations that objects continued to exist even when covered by a screen. This aligns with evidence that children of similar ages expect objects to follow regular physical norms such as continuity in shape and movement (Spelke and von Hofsten, 2001).

Similar to Spelke's core knowledge theories (Spelke and Kinzler, 2007), Susan Carey's work on conceptual development has introduced the notion of "conceptual restructuring" (Carey, 2000). While the latter does support the existence of innate structures that promote conceptual development, she considers that this is not sufficient to explain the complexity of some concepts, and thus qualitative, rather than quantitative change needs to occur. According to Carey, conceptual change happens when young children exchange intuitive or naive theories for more complex scientific ones that often require instruction to fully emerge (Carey, 2000; Carey and Carey, 1985).

On the other end of the spectrum from nativist perspectives, empiricist accounts assume that concepts are direct representations of perceptual/sensory experience or combinations of them, such as theories in statistical perception (Saffran et al., 1996).

Despite the ongoing debate and constructivists' attempts to surpass it, most current theories of conceptual development have a hard time sustaining radical nativist or empiricist positions when it comes to examining the evidence. In fact, most current theories agree with the existence of some amount of innate structure that is later fundamentally changed by action and experience. Taking this moderate approach model allows us to explain conceptual diversity and cross-cultural differences while accounting for similarities in the process, and as such, I contextualise this research by taking a moderate stance on this debate.

Two more relevant theories of conceptual development need to be accounted for in this section: The first is Sloutsky's contemporary theory of conceptual development. According to the author (Sloutsky, 2015, 2010), the transition from perceptual to conceptual categorisation occurs in the early childhood period. Before this transition, children rely heavily on their perception by grouping objects based on visual characteristics, such as colour, shape or size.

This theory points to the relevance of perceptual information for creating and developing concepts. Moreover, evidence from the field of developmental psycholinguistics points to manipulable objects associated with nouns being acquired earlier than those associated with verbs (Waxman et al., 2013). Why is this the case? Authors suggest that nouns have a direct physical relation: objects typically have clear physical and perceptual boundaries such that they pop out in the visual field and remain constant. As stated previously, contextual effects are highly important in manipulable concepts (Yeh and Barsalou, 2006). Thus, this evidence points to young children having very concrete early representations that are influenced by contextual cues. Savage et al. (2003) pointed to the late preschool period as the time at which concrete conceptual constructions progress into abstractions. As such, the period in which I will focus during this thesis (children aged 5 to 7 years of age) appears to be an appropriate time to focus on these sorts of developmental changes.

As situated beings living in a world that is rich in contextual cues, we use that information to shape concepts and ideas about our environment, which then help us understand our reality with increased complexity. Recent evidence from research on babies (approximately 6-9 months of age) has suggested that caregivers' tactile cues play a relevant role in their ability to form categories (Kadlaskar et al., 2020). As they grow, children are able to identify deeper and multiple patterns, which they organise into hierarchically organised concepts (Sloutsky and Deng, 2019; Sloutsky and Fisher, 2004). Thus, conceptual development is for making sense of the world, both for general learning and for knowledge transfer and generalisation, providing a more situated account of conceptual acquisition from earlier theories.

Secondly, there is Lawrence Barsalou's perceptual symbol theory of conceptual development, which is developed in the context of his grounded theory of cognition. While this theory will be further examined in section 2.4 (specifically in the context of computing education), in the larger scope of conceptual development, Barsalou posits that conceptual formation is grounded in perceptual symbols, meaning modal (sensory) simulations of physical actions (Barsalou, 2010, 2015). According to his theory, a concept is formed by storing the simulated action that was first perceived in the physical world, and thus, cognitive development harnesses bodily and motor aspects to support thought. In addition, when recalling a specific object, we not only recall the representation but also simulate in our brain the experience of the object that includes motor and modal information (Barsalou, 2021b; Barsalou et al., 2008).

Several recent studies using functional magnetic resonance imaging techniques (fMRI) have shown that tasks that require processing concepts activate brain areas associated with both motor and sensory perceptual modalities. For example, Martin (2007) showed that thinking about tool-related concepts activates motor areas in the brain, while fruit-related concepts activate visual regions concerned with colour and shape. Similarly, Pulvermüller and collaborators found that processing action words like "kick" or "grasp" leads to somatotopic activation in the motor cortex areas responsible for legs and hands (Pulvermüller, 2018; Pulvermüller et al., 2005). Moreover, behavioural studies also provide evidence for simulation-based conceptual processing: Glenberg and Kaschak (2002) provided evidence for a phenomenon they called the Action-Sentence Compatibility Effect (ACE), which showed that people process sentences involving physical actions more quickly when the direction of the described action matches their own motor responses, supporting the notion that understanding concepts involves embodied simulation. Table 2.2 summarises the theories overviewed in this section, highlighting their diverging views of the nature of conceptual development.

Table 2.2: Summary of theories of knowledge

Author	Approach to knowledge	How conceptual development occurs
Piaget	Constructivist: knowledge is the result of action	Progressively complex structures emerge as a result of innate reflexes and experience, action is key in constructing categories
Papert	Constructionist: knowledge is the result of action and can be scaffolded by artefacts.	The interaction with objects (tinkering) is key in constructing categories
Spelke	Nativist: there is a set of innate core knowledges that drive development	Innate modules interact with experience in concept development
Carey	Leans nativist: there is a set of innate core knowledges that drive development, but acknowledges the need for qualitative change	Concepts emerge from reorganising early core intuitions based on experience
Sloutsky	Leans empiricist: early concepts are perceptual and unstable, shaped by domain-general processes like attention and association	Conceptual development involves shifting from perceptual to abstract reasoning, supported by language
Barsalou	Leans empiricist: in embodied and grounded cognition, knowledge emerges from perceptual and sensorimotor experience that is grounded in physical restraints	Development through simulation of perceptual experiences and abstraction from repeated, embodied interactions

Throughout this section, I have examined relevant theoretical and empirical perspectives on the nature of conceptual development. Several of the presented authors have contextualised conceptual development in the more general perspective of cognitive development, relating these processes to both thought and language. Now, I will focus on the relation between concepts and language, and its implications for children's learning processes.

The relation between language and thought has been of interest for the learning sciences for a long time. For example, a relation can be established between some measures of children's language development, such as vocabulary, and their conceptual understanding. When it comes to their vocabulary measured in the estimated number of different words children are aware of, early childhood and the beginnings of primary education see an exponential increase. For example, studies have pointed out that most children go from knowledge of a few hundred words by age 2, by age 6, they have knowledge of between 6 to 10 thousand (Segbers and Schroeder, 2017).

However, vocabulary is not just relevant based on quantity; empirical studies on language development have shown that having more vocabulary surrounding concepts supports underlying cognitive processes such as categorisation and abstract reasoning. Bloom (2002) argued that the formation of concepts and their associated gains in vocabulary is directly related to the process of generalisation, as they are the means through which we create hierarchical structures. The author also highlighted that concepts are "useful" to us as long as they are able to describe sets of objects, as through the abstraction of utilising concepts, language becomes more efficient. In fact, the author points out that not all concepts are created equal: for example, studies by Brown (1958) pointed out that in the presence of a cat, we usually call it a cat (the basic-level category) instead of resorting to higher-level categories such as pet, animal, mammal, etc. Moreover, children have shown to acquire these basic-level categories first in their development, and this is because it seems these concepts are efficient in that they are broad enough to describe a set of elements, yet specific enough that it remains useful in situated everyday life.

Empirical research has shown that exposure to linguistic input facilitates cognitive gains. For instance, Fernald et al. (2013) found that the richness and responsiveness of child-directed speech in infancy predicted vocabulary size and processing speed in toddlerhood, which in turn predicted performance on measures of conceptual and cognitive skills. Similarly, Rowe (2012) showed that exposure to rare vocabulary during parent–child interactions at age two was a strong predictor of vocabulary and conceptual knowledge by the age of five.

In several studies (Cervetti et al., 2023; Rahmah et al., 2023; Zhang and Zhang, 2022), vocabulary acquisition has been shown to affect conceptual development and has contributed to our understanding that acquiring new words can lead to reorganising the boundaries of the categories we form. When children learn new word-labels for familiar elements, such as learning to separate between a “tuna” from “fish”, they revise their understanding of animal kinds to expand their taxonomy (Gelman and Coley, 1990).

Of particular interest for computing education is previous research on the role of expanding vocabulary in order to support abstract or relational thought. In a set of studies, Gentner

(Gentner, 2005, 2016; Gentner et al., 2011; Gentner and Kurtz, 2005) showed that acquiring relational vocabulary that prompted children to perform comparisons, such as "more than" or "less than", significantly improved four-year-olds ' performance on analogy tasks.

Certainly, it must also be considered that environmental and cultural differences have a role in this relation: studies by Hoff (2003) showed that differences in children's caregivers' speech, such as their syntactic complexity and lexical diversity, also predicted vocabulary outcomes, conceptual abstraction and verbal reasoning for children.

Thus, we must also consider the overall environment as well as the teacher's use of computing concepts to understand this complex dynamic properly. This is especially important when considering the evidence that conceptual development is flexible and often subtle perceptual changes have shown to impact children's categorisation of objects. For example, in a study by Jones et al. (1991), the mere presence of plastic eyes caused children to sort geometrical shapes into different categories. In light of this, it is worth wondering: how does teachers' use of computing concepts affect children's understanding? What is the impact of the specific properties of the concepts (sequence, loop, conditional) on children's understanding?.

Similar questions to these ones have been previously asked in the fields of mathematics: evidence in this field points out that conceptual understanding of mathematical concepts such as integral, function or derivative is associated with student's problem solving abilities in the discipline (Fyfe et al., 2014a; Luzano, 2023; Niemi, 1996).

Moreover, evidence in young children has shown that mathematical vocabulary is a strong predictor of their ability to convey mathematical ideas as well as later success (Purpura et al., 2011; Sarnecka and Carey, 2008) in addition, the comprehension of mathematical language seems to be specifically relevant for more vulnerable children: studies by Jordan et al. (1995) showed a correlation between vocabulary skills during preschool and later mathematical understanding, especially for children who came from an economically disadvantaged household. Similarly, other researchers (Durkin and Shire, 1991; Durkin et al., 2017) have pointed out that children often do not struggle as much with mathematical reasoning as with problem comprehension, which could be scaffolded through interventions that focus on strengthening vocabulary and conceptual understanding. While from a vastly different discipline, we might also point to the possible similarities with computing when considering this evidence, as both disciplines take on the challenge of introducing abstract concepts at an early age and have been rich fields in exploring the links between concreteness and abstraction. Because of this, my next section will focus specifically on the role of conceptual development in the field of computing education.

2.3.1 Conceptual development and computing education

For several decades now, computing education has not focused only on the instrumental aspects of programming and using computational tools, but also on fostering a deep understanding of the underlying concepts in computing (Lye and Koh, 2014). This is especially relevant in early years and primary education, in which the latest trends in computing education have centred it mainly in general problem-solving strategies Tedre et al. (2018) often under the umbrella term of computational thinking (Brennan and Resnick, 2012; Wing, 2017). Computing curricula around the world have emphasised the importance of conceptual knowledge. Work by Bocconi et al. (2016) examining curricula across Europe points to the fact that many countries have established conceptual knowledge as part of their mandatory curricula by focusing on students' knowledge of algorithms, decomposition, pattern recognition, sequencing, loops, among others. This is considered important in order to establish a strong foundation and foster motivation for the discipline.

A recent meta-analysis (Li et al., 2022) of 29 empirical articles, which compared the efficiency of unplugged activities (i.e., those which included tangible cards and board games to introduce children to basic CS notions) to programming exercises, found the former had a larger effect on primary-aged children's computational thinking skills, while the reverse was found for secondary students. These empirical findings suggest there might be benefits from a pedagogy which implements a transition from concrete objects to digital ones.

Previous research by Grover et al. (2019) has argued that a strong conceptual knowledge is the basis for understanding increasingly complex and abstract notions in computing. For example, the authors have argued that a good understanding of the concept of variables helps students in their understanding of expressions and abstraction. In an intervention carried out with middle schoolers focusing on the concept of variables, Grover et al. (2019) found that a pedagogical approach that drew from current knowledge from learning sciences and conceptual development supported students' understanding.

Concepts such as sequences, loops, and conditions are foundational in computing science. Understanding sequences requires that children recognise that elements in a given structure are executed in a given order. Previous studies have shown that children as young as three years of age are able to grasp notions of sequences and loops within control structures (Bers, 2017, 2020; Bers et al., 2022a), both through the use of tangible robots and block-based programming environments such as ScratchJr, a visual block-based programming environment (Flannery and Bers, 2013; Flannery et al., 2013; Kazakoff et al., 2013). Despite these promising results, other studies have shown that some children still find understanding sequences and loops difficult when first using block-based programming (Papavlasopoulou et al., 2019) and commit sequencing-related errors. For sequencing, younger children often use trial and error rather than planning to achieve a specific goal, however, the early childhood period represents a window of opportunity for interventions, as it is at this point in development that children begin to use planning and executive control for programming (Arfé et al., 2019, 2020). Similarly to sequences, understanding loops has also shown to represent a challenge, especially for novice learners.

In a recent study, Vaníček et al. (2023) found that novice pupils aged 12 presented several programming misconceptions while using loops, but these were heavily influenced by the programming environment utilised as well as the task presentation. Thus, it is worth examining whether simple activities targeted at early childhood and the early years of primary education could scaffold the building of these concepts and build a solid foundation for later programming. For example, (Bers et al., 2014) proposed using activities such as dances, clapping games or rhymes to foster simple representations of repetition for young children.

Lastly, understanding conditions requires children to have a basic level of causality. Previous research has shown that effective practices for introducing children to the notion of condition can benefit from being grounded in their everyday experiences (for example, understanding the causal relations between everyday events through the use of if-then verbal statements). However, when applied to programming, especially in abstract or symbolic forms, many learners struggle to interpret how conditional logic affects program flow (Lye and Koh, 2014; Rich et al., 2017). Conditional logic is closely related to causal reasoning in that while reasoning allows us to understand the mechanisms behind logical statements, conditional logic is the final implementation of these reasoning processes. Next, I will discuss the role of causal reasoning and its relation to conceptual development in CS.

Gelman and Kalish (1993) proposed that understanding causal relations is central to children's creation of abstractions through context cues, which facilitate their identification of regularities. According to Siegler et al. (2011), early in their development, children classify objects into three main categories, which include inanimate objects, people and other animals. Some authors, such as Spelke (2016), have called this a "theory of physics" (that of inanimate objects,) a "theory of psychology" (that of people) and a "theory of biology" (that of other living things such as animals). Nativist authors propose that we are born with a rudimentary theory of physics and understanding of how objects move through space. Wellman and Gelman (1998) proposed that the first theories on psychology for children were developed around 18 months, where children are first capable of understanding that another's actions reflect their wants. Lastly, we develop an understanding of how other living objects work around 3 to 4 years of age, for example, 3 and 4 year olds children are able to infer that animals move by themselves (Gelman, 2003).

These main categories are the foundations of the formation of categorical hierarchies. That is, our mental representation of concepts within concepts and the way we relate and connect them.

Research into categorical hierarchy in children reveals that categorical hierarchies exist even when they are very young. Studies using the habituation paradigm show that even infants possess a rudimentary grasp of hierarchical categories, as evidenced by their ability to distinguish between basic-level and superordinate categories Gelman and Coley (1991). For instance, children are able to classify objects into broader categories and recognise the relationships between these categories, such as identifying that a robin is both a bird and an animal (Sloutsky, 2010). Thinking about concepts and how they relate to each-other crucial for causal reasoning.

As children categorise and organise information hierarchically, they begin to recognise patterns and relationships that underpin causal mechanisms. These abilities emerge during early childhood. For example, authors Sobel and Kirkham (2006) presented 19- and 24-month-olds a box called a “blicket detector” that played music when a type of object called a blicket was placed on it. They then proceeded to place two different objects (A and B) in the box and just played the music only when object B was inside. When asked which object was the "blicket", 19 months old showed no differentiation between object A and B. However, by 24 months of age, children were consistently picking object B as the blicket, thus successfully making the inference that if music plays when object B is inside, it must be the correct one. In line with this, Bonawitz et al. (2010) found that children’s understanding of causal mechanisms was significantly enhanced when causal language was used during explanations, supporting the idea that linguistic framing plays a role in inferential processes. Language can thus serve as a scaffold for reasoning about the abstract relations that abound in computing.

Taken together, this evidence points to conceptual acquisition starting from a very young age and emerging from perceptual capabilities that, with time, increase their complexity and create feedback loops which allow us to use the concepts we acquired to construct a deeper understanding of the world around us. Thus, our acquired concepts also help us make sense of the world and become lenses we use for understanding as well.

Understanding computing concepts demands that young children develop a mental representation of how their program works and the causal relations behind it. For example, when working in ScratchJr, a visual, block-based programming environment which which represents commands through pictograms such as arrows (Flannery et al., 2013; Portelance et al., 2016; Stamatios, 2024), children must understand the causal relation between their programming commands and the sprite’s movements on the screen. Empirical work in the field of science education has shown that there’s an association between children’s causal reasoning skills and their science literacy: in their study, showed that children between the ages of 3 and 5 who scored high on measures of causal inference had better science skills even when controlling for general cognitive ability Bae et al. (2023). This suggests that children who can reason about causal relationships are better positioned to engage in systematic thinking about processes, which is a key aspect of science education but also of computer science education.

In the following section, I will expand on the relation between conceptual development and the support of a higher-order cognitive skill, such as meta-cognition and its implications for learning in computing.

2.3.2 Metacognition and conceptual development

Metacognition has been traditionally defined as “thinking about thinking” (Flavell, 1979), a complex skill which involves both meta-cognitive knowledge (i.e., our self-appraisal regarding our own learning) and meta-cognitive regulation (i.e our attention to task performance, our selection of appropriate learning strategies, our ability to evaluate and revisit our learning goals and our planning and monitoring of tasks) (Brown, 1987). Recent meta-analyses have shown that meta-cognitive skills are a predictor of a student's academic achievement, even when controlling for general intelligence measures (Ohtani and Hisasaka, 2018; Zheng, 2016). Zohar and Barzilai (2013) defined meta-cognitive prompts as "questions, cues or probes that are introduced by the teacher with the aim of fostering meta-cognitive thinking".

McAlpine et al. (1999) proposed a model of meta-cognition composed of: goals, knowledge, action, monitoring, decision-making, and tolerance. According to the authors, goals are the drivers of both action-oriented behaviours by the students and instructional decisions by teachers. Establishing clear learning goals is an important practice during teaching and instruction. In this model, knowledge is represented in relation to action, defining a constant interplay between the external enaction of goals (action) and the ever-updating beliefs and cognitive structures represented by knowledge. The links between action and knowledge are represented in this model by monitoring and decision-making. These activities entail the processes by which information is assimilated and updated by students and are akin to Brown's idea of metacognitive regulation. Lastly, tolerance refers to an individual's threshold of expected outcomes, which determines their decision to change or continue their behaviours.

An important aspect of monitoring specifically relevant to science education is visualisation. This consists of forming a mental image or representing an object or process (Gilbert, 2005), and it's particularly relevant in disciplines where it is highly valuable for pupils to be able to change between different modes of representation, including the concrete, the visual, the symbolic and the verbal. In fact, Locatelli et al. (2010) used the term meta-visualisation to refer to this step in the meta-cognitive process related to the learning of a scientific discipline such as chemistry. In computer science, visualisation is very important as ultimately most of the abstractions involved will be carried out in a virtual setting (Fouh et al., 2012).

Visualisation has been defined as a metacognitive skill, as it is a part of the construction of mental models, which aid in the explanation of concepts and how they relate to each other. Moreover, it has shown to be a successful practice in improving conceptual understanding in computer science (Twissell, 2018). It is possible to see that the multiple components in McAlpine et al. (1999)'s model could take different forms depending on the concreteness of the presented activities: it is possible to formulate the hypothesis that enacted and physical activities will ease the visualisation and monitoring processes, while mental and formal activities present the greatest distance between action and knowledge. Thus, presenting students with visualisation and monitoring prompts throughout activities might scaffold their understanding.

Specifically, when working with physical objects, it follows that meta-cognitive prompts aimed at supporting students' visualisation as well as their meta-cognitive knowledge would be appropriate, while as activities increase in complexity and abstraction and the conceptual knowledge starts to involve understanding their inter-relations, meta-cognitive prompts aimed at monitoring as well as knowledge become more important.

Metacognition and conceptual understanding have a reciprocal relation, which has, in part, been targeted in the previous section. As they acquire more concepts, they are, in turn, more capable of explaining their own thought processes, which allows them better problem-solving and planning strategies. Several empirical studies have supported the view that language and vocabulary are precursors for meta-cognitive expression. Astington and Olson (1995) found that children's use of mental state terms was closely related to their performance on tasks requiring reflection about one's own thinking, such as memory monitoring and uncertainty judgment. Similarly, Kuhn et al. (2000) observed that children who could verbally justify their problem-solving approaches using terms like "I figured," "I tried," or "I realised" performed better on tasks involving meta-cognitive control, suggesting that the linguistic expression of thought strengthens meta-cognitive regulation. Moreover, this introduces a positive feedback loop in which children who are better at communicating their meta-cognitive processes in turn organise their thoughts and actions better and are thus in a better position for learning in the future. This also has shown evidence of working in the opposite direction: interventions that targeted improving children's vocabulary had positive effects on their meta-cognitive reflection (Boulware-Gooden et al., 2007).

Developmental research shows that it is during preschool and early primary that children begin to exhibit meta-cognitive behaviours such as pausing to assess a task, systematically asking for help when in doubt or revising an approach when they recognise a mistake (Chen et al., 2025). These findings indicate that the roots of meta-cognitive monitoring and control are present in early childhood (Chatzipanteli et al., 2014; Maric and Sakac, 2020).

Previous research in computing education shows that linking meta-cognitive processes explicitly to computing science tasks appears to enhance learning outcomes (Lishinski and Yadav, 2019; Prather et al., 2020a; Wang et al., 2024; Zohar and Barzilai, 2013). In a study integrating computational thinking and meta-cognitive awareness in a STEM education context, primary children who were prompted to reflect on their strategy use when coding or solving tasks showed improved performance, indicating that meta-cognitive scaffolding supports conceptual understanding and transfer (Markandan et al., 2022). Although much of the meta-cognition research in computing has been conducted with adult participants or adolescents (Li et al., 2024; Loksa et al., 2022; Parham et al., 2010; Prather et al., 2020b; Shaft, 1995), work regarding its role on younger children is emergent (Yadav et al., 2022).

2.4 Grounded cognition theories and their relation to conceptual development

Grounded cognition constitutes a theory of cognition which posits that our thoughts are shaped and influenced by dynamic actions stemming from our bodily experiences and perception as well as our interactions with our environment. According to Barsalou (2010, p.717):

> The environment, situations, the body, and simulations in the brain's modal systems ground the central representations in cognition. From this perspective, the cognitive system utilises the environment and the body as external informational structures that complement internal representations. In turn, internal representations have a situated character, implemented via simulations in the brain's modal systems, making them well-suited for interfacing with external structures. Barsalou (2010, p.717)

Central to this definition of cognition is the role of the brain's modal systems in creating mental representations. This means that representations are not merely transduced from sensorimotor representations to symbols, but that modality (i.e., visual, auditory, etc.) specific states are captured by memory systems. According to grounded cognition, the brain later simulates the concept in the absence of stimuli. Grounded cognition is often considered as a response to purely cognitivist notions, which conceive representations as amodal (not specific to an individual sensory system) and symbolic (symbols are used to create a mental representation of an object or experience) (Shapiro and Stolz, 2019).

Bermúdez (2014) posited that the notion at the heart of cognitive science is the idea of the mind as an information processor. The conjunction of research and ideas in different fields such as psychology, philosophy, linguistics and computer science during the 1950s and 60's would later be called by authors as the "cognitive revolution". This shift in paradigm was, as Miller (2003) has explained, a counter-revolution in itself, as it emerged as a challenge to the previous behaviourist notions of action stemming from complex chains of stimuli and response, and the limitation of psychology to the study of observable behaviours.

Authors from very different backgrounds became key figures in this shift of focus towards the mind. Alan Turing's notion of a Universal Turing Machine provided a theoretical model for cognitivists to posit that the mind is a series of computations performed algorithmically in the brain (Turing, 1936).

The underlying notion that the mind consists of a series of computations in the brain was also reflected in seminal works of the cognitive revolution such as Chomsky's in linguistics which posited the innateness of grammar (Chomsky, 1959) or Fodor's thesis on the modularity of cognitive systems (Fodor, 1983) which considers cognition as a set of computations located in the brain which could be completely separated from the body as a vessel.

As for grounded cognition, while authors have argued its constitutive ideas have been present long before the existence of cognitive science as a field (Barsalou, 2010; Barsalou et al., 2008), the work of Varela et al. (1991) in which they define the perception-action loop while considering the repercussions of different bodily and perceptual configurations for cognition is often marked as a pivotal moment for contemporary grounded cognition. In this view, the environments and the cognitive mechanisms that perceive it determine each other (Pasquinelli, 2006), forming a complex system of interaction.

Much of the work on grounded cognition references a subset of its field called embodied cognition (Shapiro and Stolz, 2019), however, I will refer to the broader term of grounded cognition to encompass not only the body's implications for cognition but also the physical environment (interaction with objects, other beings and physical settings), modalities of internal and external perception, and lastly culture and the social environment (Barsalou, 2020).

The inclusion of these aspects is sometimes referred to in the literature as 4E cognition: cognition that is embodied, embedded, enactive, and extended (Newen et al., 2018).

Embodied cognition consists of the notion that our perception and thought are highly influenced by our bodily experiences, and that dynamic actions such as movement and object manipulation have an effect on our understanding of the world around us (Leitan and Chaffey, 2014). Proponents of embodied cognition argue for the constitutive role of the body in forming cognition. However, there are several nuances among authors in embodied cognition about the precise role of the body for cognition and, more importantly, for concept representation. Gallagher (Gallagher, 2014, 2018) described two distinct consensuses in the literature: those referring to "weak" vs. "strong" embodied cognition. Proponents of strong embodiment argue for the constitutive role of the non-neural body in cognition. Moreover, some proponents of strong (or radical embodied cognition) supported by evidence from fields such as bio-inspired robotics (Brooks, 1990), have suggested that seemingly cognitively complex actions, such as movement coordination, might not need a brain to be fulfilled by an actuator.

Proponents of weak embodiment, on the other hand, argue for the existence of body-formatted representations that nonetheless exist in the brain. Thus, they recognise the feedback loop formed by the body in shaping cognition, but the brain is where it takes place. Goldman (Goldman, 2013a,b) cited studies concerning mirror neurons to support this claim. In these studies (Rizzolatti and Sinigaglia, 2010) it was shown that the mere act of observing the performance of a given task by others caused activation in the same premotor areas which are involved in the actual execution of the task. Thus, humans (and other primates, see: Bonini (2017); Maranesi et al. (2017)) "mirror" the actions in their brain, which Goldman posited was congruent with the existence of body-representations. Moreover, these findings are not limited to the motor system, as similar studies involving observing emotions have shown to recruit similar visceral-motor and sensory-motor areas (Gallagher, 2018; Goldman and De Vignemont, 2009).

Embedded cognition refers to the role of the physical environment's interaction with individuals in shaping cognition through action and perception. Newen et al. (2018) argue that cognition is embedded if it partially depends on extra-bodily processes, meaning they define embedded cognition as a more moderate claim to embodiment, as it recognises the importance of the effects of environmental interaction but lacks constitutive weight. However, regardless of this notion, which considers embedded cognition in relation to the axis of how radical claims on embodied cognition are, other authors have used the term "embedded" to stress the role of environmental characteristics on cognition. Thus, embedded cognition broadens this view and highlights the importance of situating cognitive action.

Enactive cognition focuses on the role of movement and action, its main thesis being that active engagement is a necessary condition for cognition. The term was popularised in the influential works of Varela et al. (1991, p. 9) who used it to define cognition as the "enactment of a world and a mind on the basis of a history of the variety of actions that a being in the world performs". This means that it matters how we engage with the environment and the actions it allows us to take. The term affordances has been used to refer to the possibilities for action given to us by objects or other environmental elements (Gibson, 1979). Moreover, Varela et al. (1991) defined perception as a form of action. This means that perception should not be considered a passive reception of information but as actively engaging in sense-making processes. This extends not only to current action but also past-action and the way previously held experiences shape our expectations of the world and future events (O'regan and Noë, 2001).

Finally, the term "extended cognition" (Newen et al., 2018) has been used to refer to the idea that, upon being able to interact with certain external environmental resources (for example, technological tools such as computers or smartphones), cognition should not be conceived just in the domain of the brain. Proponents of extended cognition argue for the possibility of cognitive processing happening outside the brain, for example, when we use technology to store large amounts of information that our brain is not capable of keeping and would not be able to access. Explicitly, Kiverstein (2018) argues that from this perspective, elements such as smartphones and other mobile technologies, which are thoroughly interwoven in our everyday lives, have a profound impact on our day-to-day cognitive processes and are considered by these authors as part of our minds. These notions thus clash with the previously mentioned view of embedded cognition, where, despite environmental and bodily factors being of importance to represent cognition, the brain still was the agent performing cognitive action. Broadly, the debate between the notions of embedded and extended cognition pertains to the localisation and conceptualisation of cognition. While the former might be more in line with traditional cognitivist ideas, the latter calls for challenging the delimitations between brain, body and objects and understanding the interplay between them as a dynamic system of interactions.

In 1992, Rizzolatti and collaborators identified, while studying primates, what would later be coined as "mirror neurons" (Di Pellegrino et al., 1992; Rizzolatti and Sinigaglia, 2010). That is, the observation of neural activation in motor areas not only while the animal was performing a motor activity, but also while observing the performance of various actions by a third party (Di Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996). These findings would soon be replicated in humans and become an extraordinary contribution to our understanding of how we encode movement and behaviour. It is through this mechanism that some authors have argued mirror neurons are involved in the process of embodied simulation of action (Aziz-Zadeh et al., 2006) and are important for our understanding of others' intentions and our social cognition (Gallese et al., 2004). These authors have theorised that we also make use of these representations grounded in action for language:

> The communication of concepts from the mind of one speaker to the mind of another could be accomplished with great immediacy if language utilises the same neural representations of a concept that would be activated by direct experience of the same concept (Aziz-Zadeh et al., 2006, p.1821).

This is, in fact, one of the central propositions of grounded cognition: that meaning (i.e semantic knowledge) is represented through action (Buccino et al., 2005; Goldberg et al., 2006). Experiments and neurophysiological studies in this area have tested subjects' understanding of action words and found a correlation between motor activation and action word processing, even when the subject is passive. For example, Hauk et al. (2004); Hauk and Pulvermüller (2004) and collaborators have reported these findings in an fMRI study. These findings are not restricted to visual perception but include, for example, information from emotional processing (Vigliocco et al., 2009). According to Barsalou (Barsalou and Wiemer-Hastings, 2005), representation is thus modally represented, spans all perceptual forms and is represented in the brain in a distributed way and is moulded and influenced by both direct experience, imagination and affected by attentional and motivational factors (Bermeitinger and Kiefer, 2012; Kiefer and Trumpp, 2012).

Behavioural data supported the idea that both action and manipulation are linked to conceptual comprehension: early experiments on word processing found that concrete concepts present a processing advantage over abstract concepts (Barsalou and Wiemer-Hastings, 2005; Binder et al., 2005; Crutch and Warrington, 2005) known as the "concrete effect". In fact, the representation of abstract concepts has been one main contentious points and challenges for grounded and embodied cognition. Despite this, Kiefer and Trumpp (2012) proposed that abstract concepts might only differ from concrete ones in that more lexical associations and contextual information are needed to create understanding (Barsalou et al., 2008). Barsalou (2021a) highlighted that the formation of abstract concepts might not be a challenge exclusive to grounded cognition, as the link between language and the semantics of abstract knowledge is a challenge of amodal perspectives as much as for grounded cognition and points to the role of a more cultural perspective. Thus, his recent theorisations about a situated action cycle (Barsalou, 2020) encompass a more holistic approach where abstract concepts relate to internal self-relevant and affect.

In light of this evidence, several authors have proposed that the grounded cognition perspective might find a more applied setting in the field of education (Faella et al., 2025; Hegna and Ørbæk, 2024; Kosmas and Zaphiris, 2018; Kwon et al., 2024; Leitan and Chaffey, 2014; Shapiro and Stolz, 2019). This is because the explicative framework of grounded cognition is, like every cognitive theory, a system of learning. Thus, it is reasonable to argue that the findings in grounded, embodied and enacted cognition have the potential to be leveraged to scaffold instruction. In light of this, instructional strategies based on these principles have been proposed for all sorts of disciplines. Here, I will mention two: mathematics and science instruction. Research on these fields indicates that these learning experiences have the potential to promote understanding, especially for novice learners (Abrahamson and Trninic, 2011, 2015). Instructional practices such as concreteness fading (beginning instruction with concrete objects as a scaffold and gradually prescinding of them) have gained relevance in empirical research (Kiefer and Trumpp, 2012).

In maths, these strategies have been implemented when tasks require high levels of abstraction as a way to provide contextual cues. In a classic study by Rittle-Johnson and Alibali (1999), students were taught mathematical equivalence using concrete, pictorial, and abstract representations, an approach inspired by Bruner (Bruner, 1960, 1966) and Vygotsky's (Vygotsky, 1934a,b) ideas, which will be further discussed in the upcoming section. Their results indicated that students who engaged in concreteness fading showed better conceptual understanding and transferability of knowledge. Since then, several studies have found similar results (for a detailed review, see Fyfe et al. (2014b)). In mathematics learning and numerical cognition, researchers have found a link between finger counting (an inherently embodied activity) and number processing (Fischer and Brugger, 2011; Lindemann and Fischer, 2015; Soylu et al., 2018). Moreover, integrated perspectives in mathematics instruction have proposed a dynamic ecological perspective (Abrahamson and Sánchez-García, 2016; Abrahamson et al., 2016) which calls to the work of Bronfenbrenner (2000) which I will expand upon in section 2.4.2.

2.4.1 Barsalou's theory of grounded cognition:

In the previous section, I provided an overview of what I referred to as grounded cognition theories in a broad sense, encompassing several theories of cognition that include the grounded, embodied, enacted, embedded and extended views, also referred to by Newen et al. (2018) as "4E cognition". Here, I will focus specifically on grounded cognition theory as conceptualised by Lawrence Barsalou (Barsalou et al., 2008), given that it is specifically relevant theoretically to the pedagogical model I aim to evaluate in this thesis and which will be expanded on below.

As previously mentioned, Barsalou's work on grounded cognition theory is novel in regard to classic cognitive science postures in which the mind is seen as an information-processing agent that is separated from the body's modal sensations (Bermúdez, 2014). On the contrary, Barsalou's proposition that cognition is grounded means that it is inevitably restricted by the conditions of the body, the environment and the action being performed, as well as any interactions between these elements (Barsalou, 2015; Barsalou et al., 2008).

Barsalou's work is especially relevant for this thesis since not only has the author focused his inquiry on grounded cognition, but he has also focused on the topic of conceptual development, specifically wondering the implications a grounded cognition has for concept formation and representation (Barsalou, 2015, 2019; Barsalou and Wiemer-Hastings, 2005). Thus, as I previously articulated, concepts are, in his view, not just abstract representations but grounded simulations of previous actions or experiences which involve the body's sensory and motor systems (Barsalou, 2021a, 2023; Barsalou and Wiemer-Hastings, 2005).

The fact that concepts are thus attached to real-world actions and simulations of real-world actions in the brain means that our knowledge about concepts necessarily comes from a highly situated environment: in his view, our knowledge about concepts is subject to the restrictions of the environment. Thus, this gives the possibility for context-sensitive conceptual representation, which he referred to as "situated conceptualisations" (Barsalou, 2003, 1982; Prinz and Barsalou, 2014; Yeh and Barsalou, 2006). These situated conceptualisations are akin to concepts, yet the notion reminds us that these concepts are bound by specific objects, actions, environments and introspective states (Barsalou, 2009, 2015; Lebois et al., 2020; Yeh and Barsalou, 2006).

Based on these tenets, one might wonder about the nature of the process of abstraction, given that if concepts are situated, then it follows some characteristics of the situation must be left behind to achieve an abstract representation or concept, or, as Pines (1985) defined, a package of meaning that captures regularities. Barsalou proposes that the process of abstraction happens through a mechanism he calls the "perceptual symbol systems" (Barsalou, 1999, 2005). This means that when we encounter an experience, for example, seeing a cat, our brain stores perceptual patterns of that experience that later on are reactivated in our memory when we think about seeing a cat. Importantly, these patterns are modal, meaning that they are linked to specific sensory information (Barsalou, 1999). These theoretical proposition is supported by empirical evidence showing brain motor activation during exposure to action-related concepts even when participants are completely still (Adolph and Hoch, 2019; Barsalou, 2003, 2020; Francis et al., 2016). Given repeated perceptual experiences, these patterns become increasingly familiar and are thus able to become generalised while still originating from perceptual information.

Integrating his theoretical approach to cognition with his empirical work, Barsalou introduced the Situated Action Cycle (Barsalou, 2020) as a comprehensive framework of how these situated elements interact in order to produce our understanding of the world around us. The model describes our cognitive abilities as a conjunction of elements organised in a dynamic loop that is integrated in five sub-domains: firstly, the modalities that organise external and external perception (examples of external perception are vision, audition, olfaction, while internal perception involves interoceptive information), secondly, the characteristics of the body, meaning the role of our extremities, height, motor abilities, immune system, heart resistance and a multiplicity of other physical restraints of our body; thirdly, the physical setting that surrounds us, which encompasses the restrictions of our indoor and outdoor settings as well as the objects we have available to interact with; fourthly, our cognitive abilities, meaning our attention, working memory capacities or previous knowledge among other elements; and lastly our social environment that encompasses our sense of self, our perceived agency, social interactions with others and cultural effects on our behaviour. These five domains are only theoretically defined, as according to Barsalou (Barsalou, 2020) and following other systemic perspectives (Bronfenbrenner, 2000; Bronfenbrenner and Morris, 2007), in practice, these elements are not separable when accounting for experience and behaviour.

Thus, the situated action cycle represents the dynamic interactions between these sub-domains during the process of perceiving and simulating concepts.

Thus far, I have identified the key aspects of grounded cognition theory and aimed to provide an overview of how conceptual development happens from this theoretical perspective. As stated, the role of simulating real-world action is key for conceptualisation (Barsalou, 2010; Barsalou et al., 2008). However, I will now focus on the implications this perspective has for computing education research and specifically, I will try to shed light on current practices in computing instruction that can be theoretically related to grounded cognition theory. From a practical perspective, it is worth wondering which instructional practices best align with this theory from an educational point of view. Some authors have previously discussed the possible implications of grounded cognition for education (Shapiro and Stolz, 2019), however, only a few studies have focused on the theory's role for computing education in particular (Kallia and Cutts, 2022; Trory, 2016; Trory et al., 2025).

The first aspect that can be identified as relevant from an educational perspective is the role of motor action during the learning of computing. In particular, the use of gestures has been a previously explored aspect that might facilitate conceptual learning.

If I take mathematics instruction as an example, previous evidence from Alibali and Nathan (2012) showed that when adults gestured during explanations of algorithmic processes in algebra, their ability to articulate and refine complex ideas improved, suggesting that physical movement might improve conceptual retention. Similarly, Novack and Goldin-Meadow (2015) showed that adults who physically enacted sorting performed better on subsequent tests of algorithmic reasoning than those who only observed demonstrations or verbal explanations. Novack and Goldin-Meadow (2015) points to gestures as an indicator of the learner's understanding, as it is linked to representational action.

For children, this association seems to have even stronger support. In a classic study, Church and Goldin-Meadow (1986) observed that children who spontaneously used gestures to describe problem-solving strategies in coding-like tasks were more successful in solving similar problems later, indicating that gestures may facilitate connecting concrete actions to abstract ideas. Not only that, but the authors identified gestures as an indicator of transitional knowledge, meaning children are in the midst of building their conceptual understanding. Work by Sullivan and Bers (2016) found that young children engaged in robotics activities that incorporated gesture-based interactions showed greater improvements in sequencing and debugging skills than those who learned through traditional methods. While these results are promising, further studies are needed in order to establish the congruency between concept and gesture. As demonstrated by Manches et al. (2020), adult participants often alluded to both physical and motion gestures in their explanations of computing processes. A second instructional strategy that can be identified as aligned with grounded cognition theory is the interaction with concrete objects for learning. Specifically, concrete objects and activities that are congruent with the concept one aims to learn

(Barsalou, 2010; Kallia and Cutts, 2022).

Research exploring the use of concrete materials in computer science has a long history and has shown significant benefits across different age groups. Among adults, studies indicate that hands-on manipulation of physical objects to represent computational concepts can improve understanding and engagement. For instance, in a study by Curzon et al. (2014), adult learners who participated in unplugged activities exhibited better comprehension of abstract programming principles. The tactile experience was found to support cognitive processes by providing tangible analogies for intangible concepts (Lye and Koh, 2014).

Furthermore, a review by Grover and Pea (2013) demonstrated that unplugged activities encouraged active learning and collaborative problem-solving, which are critical for mastering complex computer science topics at the adult level.

For young children, studies have shown that concrete materials can effectively introduce computational thinking skills before children have advanced reading or typing abilities. For example, in a controlled experiment, Bers et al. (2014) found that preschoolers who engaged in unplugged robotics activities using physical blocks to sequence instructions significantly improved their understanding of sequencing and logic compared to peers who only observed digital tasks. Similarly, Weintrop (2016) found that elementary school students participating in unplugged exercises such as maze navigation and pattern recognition exhibited enhanced problem-solving abilities. A similar trend emerges when examining other tangible materials, such as floor robots. In a study by Kazakoff et al. (2013), children who took part in an intervention aimed at promoting computational thinking through floor robots improved in their sequencing skills. The physical embodiment of programming the robot to move was argued to provide salient feedback for children and be a motivating tool that effectively enhances their engagement (Bers, 2017). Moreover, floor robots encourage a collaborative learning environment, providing opportunities for discussion and peer instruction, which could have further positive effects for conceptual understanding (Resnick et al., 2009). Similarly, several studies (Choi et al., 2024; Critten et al., 2022; Papadakis and Kalogiannakis, 2022; Seckel et al., 2023) suggested that preschoolers using programmable floor robots such as the Bee-Bot developed significant improvements in sequencing, spatial reasoning, and cause-and-effect understanding compared to children who did not engage with such technology.

Thus, when I examine the empirical evidence for instructional practices which can be identified under the umbrella of being inspired by grounded cognition (that is, integrating the body, concrete objects or notions such as concreteness fading into computing instruction for young children) this indicates that these interactions might affect children's performance and understanding of basic computing concepts such as sequences, loops and conditionals, among others (Bers, 2021, 2017, 2020). Moreover, embodied and tangible computing environments tended to have an impact on affective aspects of learning, such as motivation or engagement. In their study, Wang, Zhong and Pan (2017) found that students using physically embodied robots showed higher engagement and expressed more interest in continuing learning computer science.

2.4.2 Grounded cognition and its connection with systemic and socio-cultural perspectives

Developmental science centres around a set of theories known as developmental systems theories (Gottlieb, 1991; Hood et al., 2010; Lerner, 2012; Lerner and Lerner, 2019; Overton, 2013). These theories understand development as a probabilistic multi-level phenomenon and aim to capture the complexity of the interrelation between various variables. As argued in section 2.2, part of the objectives for this thesis is to explore how children gain conceptual understanding, specifically in computing, from a situated perspective, but also taking into account their trajectories towards this goal. As such, this thesis aims to take a developmental perspective on conceptual understanding by exploring children's processes through time. Part of taking a developmental perspective means delving into the theoretical underpinnings of developmental science: developmental science is an intrinsically interdisciplinary perspective which accounts for the biological, psychological, cultural and environmental factors (Bronfenbrenner, 1977).

In the previous section, I focused on the implications of grounded cognition theory for conceptual understanding and explored some practices in computing that might theoretically link instruction to grounded cognition. Here, I argue that in order to gain a deeper understanding of these processes it is necessary not only to take a dynamic approach within the individual participants (such as that presented by grounded cognition theory, which highlight the dynamic aspects of cognition, affect, the body, the environment and perception), but also complement this perspective with a dynamic approach that encompasses broader social and cultural context that is inherent to an educational setting. In order to do this, I will elaborate on Bronfenbrenner's ecological systems theory (Bronfenbrenner, 2000; Bronfenbrenner and Morris, 2007), aimed to highlight the individual's contexts of socialisation, its complementarity to grounded cognition theories and its implications for the research conducted in the context of this thesis.

Urie Bronfenbrenner (Bronfenbrenner, 1977) criticised previous experimental approaches as "the science of the strange behaviour of children in strange situations with strange adults for the briefest possible periods" (Bronfenbrenner, 1977) and advocated for a shift toward more naturalistic, observational methods. He considered his approach to be both an expansion and a convergence of observational and experimental paradigms, rejecting the notion of a dichotomy between these approaches. He defined his ecology of human development as: "the scientific study of the progressive, mutual accommodation, throughout the lifespan, between a growing human organism and the changing immediate environments in which it lives, as this process is affected by relations obtaining with and between these immediate settings, as well as the larger social contexts, both formal and informal, in which the settings are embedded." (Bronfenbrenner, 1977, p.514).

His theory emphasised the complex interactions between an individual's situated systems. To illustrate this, he proposed a classification of five systems that progressively encompass aspects of reality and nest within each other, as represented in 2.1.

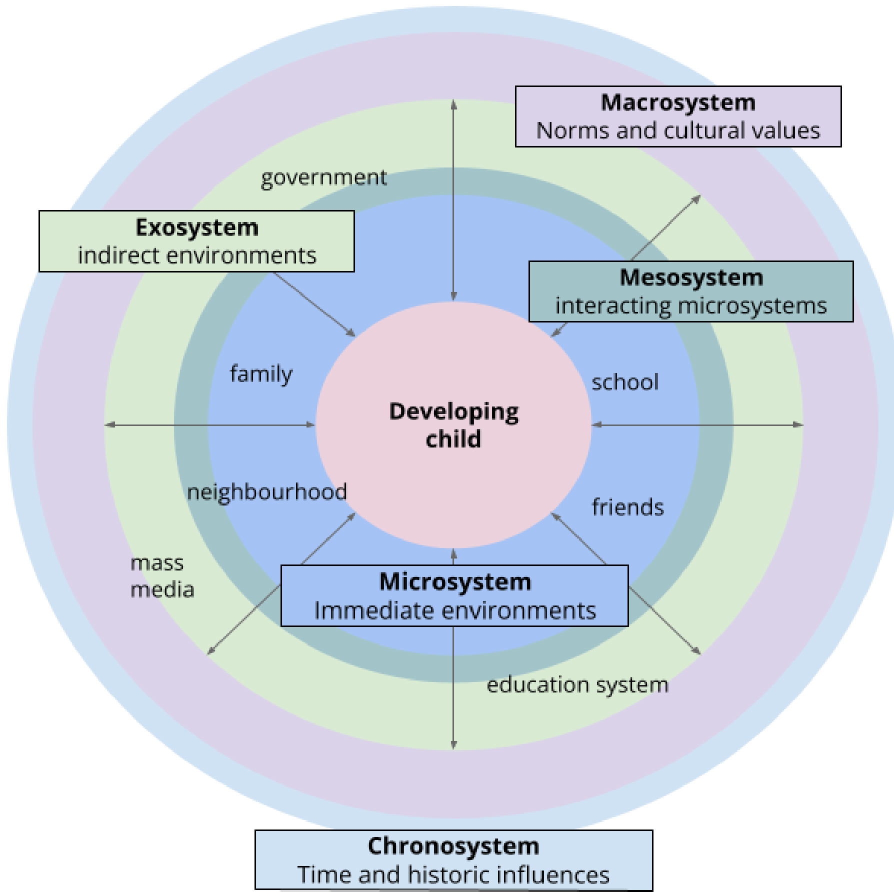


Figure 2.1: Bronfenbrenner's model. Adapted from Nicholson and Dominguez-Pareto (2019).

In the microsystem, Bronfenbrenner and Morris (2007) locates the relationships between the individual and their immediate environment (e.g., family, school, peers, neighbourhood). The mesosystem is comprised of the interconnections between microsystems and their respective settings (e.g., family and teachers). Meanwhile, the exosystem is composed of those settings and institutions that indirectly interact with the individual but significantly influence their micro and mesosystems, such as job culture, mass media, government agencies, or societal infrastructure.

At the macrosystem levels, there are all the societal structures that impact most institutions and exhibit recurring cultural patterns, including explicit structures like laws and implicit structures like ideology or customs. Lastly, the chronosystem alludes to the pattern of environmental events characteristic of a specific moment in the lifespan, such as changing societal rules or the consequences of war.

Bronfenbrenner's theory emphasises that while these systems serve as a classification methodology for studying human development, they are inherently interconnected and must be considered interdependent entities. This underscores the situatedness of the field of study and provides a framework for analysing its interconnected nature (Bronfenbrenner, 1977; Bronfenbrenner and Morris, 2007).

Given that all research is limited by situational constraints, it would not be expected for a single study or research project to encompass all the levels defined in Bronfenbrenner and Morris (2007)'s model. However, the model influences my research through providing a theoretical perspective that complements grounded cognition theory but extends its view towards the broader social and cultural context: as such, incorporating this theoretical perspective allows me to focus on the context of the interrelation between children and teachers, children and their school, and part of their culture. As this thesis is focused on exploring young children's conceptual understanding of computing, it is firmly situated within the micro-system; albeit inevitably, during the learning process, it is expected that aspects of the macro-system, such as cultural aspects, or even the exosystem, such as technology availability for the classroom, are at play.

In their review of sociocultural cognition theories in CS education, Tenenberg and Knobelsdorf (2014) point out that computer science has historically adopted a cognitivist perspective, with this underlying notion present in significant contributions in the field. However, CS education researchers and practitioners have recently begun to incorporate elements that challenge cognitivist notions to incorporate sociocultural perspectives in CS. The need for the inclusion of sociocultural perspectives stems from vast evidence pointing to how cultural and environmental factors affect learning and cognitive processes in CS. For example, Sentance et al. (2019) used a sociocultural perspective to account for how teachers regulate mediated activity from a Vygotskian (Vygotsky, 1934b) perspective.

According to Tenenberg and Knobelsdorf (2014), these theories "view minds as cultural products, biologically evolved to be extended by tools, social interaction and embodied interaction in the world. Learning, under this perspective, is viewed as tool-mediated participation in the ongoing practices of cultural communities" Tenenberg and Knobelsdorf (2014, p.2) These authors draw from Vygotskian ideas to propose that cognition is mediated by both material and cultural tools, such as language and other schemes (Vygotsky, 1934a).

Evidence from both mathematics and computer science education supports this idea, as pupils use the affordances of concrete materials to solve problems more effectively (Sarama and Clements, 2009a,b; Sowell, 1989) Moreover, they propose that the mind is in constant dialogic interaction with the world, a notion that is congruent with Barsalou's proposal for considering the situatedness of conceptualisation (Barsalou, 2015).

Taking into account these systemic perspectives, I am able to observe several complementary points that merit considering taking an integrative approach towards these theories:

- a) Grounded cognition's perception-action loops highlight the intertwining of factors in development. Thus, it acknowledges that cognitive processes are not only mental but are embedded in a continuous loop of perception and interaction with our environment. Enactivist views (Gallagher, 2013, 2014; Varela et al., 1991) have argued that:

> The explanatory unit of social interaction is not the brain but a dynamic relation between organisms, which include brains, but also their own structural features that enable specific perception-action loops involving social and physical environments, which in turn affect statistical regularities that shape the structure of the nervous system (Gallagher, 2013, p.422).

As can be appreciated, this conceptualisation is intrinsically systemic, as it is supported by the idea of bidirectional associations between multiple levels of interaction.

- b) Situated action cycle and cultural implications: Grounded cognition theory emphasises the idea of cognition as being situated. According to Barsalou (2023), different cultures provide unique environments, tools, and practices that influence how individuals perceive, think, and act. Therefore, understanding cognition requires considering the cultural context in which it occurs, and this understanding of grounded cognition thus reflects the necessity for a systemic perspective.

- c) The role of language in development: grounded cognition theory acknowledges that language is not just a symbolic system but is grounded in sensory and motor experiences. As previously mentioned, language is deeply intertwined with culture, as it carries cultural norms, values, and ways of thinking Barsalou (2023). In summary, grounded cognition theory recognises that cognition is not isolated but is deeply influenced by the systemic interactions between the individual, their body, their environment, and their cultural background. By integrating these factors, a comprehensive view of CS conceptual development and how it's affected by its systemic relations can be created.

2.5 Bridging theory and practice: theoretical contributions for instruction in real-world classrooms

In this section, I will start by introducing the EIFFEL (Enacted Instrumented Formal Framework for Early Learning in Computing) as proposed by Kallia and Cutts (2022). Next, I aim to expand on the model by introducing key theoretical elements related to instruction and the practical implementation of the model, which were taken into consideration throughout the development of this research.

The Enacted Instrumented Formal Framework for early learning in computing (EIFFEL) was developed by Kallia and Cutts (2022) based on a grounded conception of cognition. The model prioritises two central aspects in its organisation of CS instruction: action concreteness (according to their level of abstraction, actions are classified as enacted, instrumented or symbolic) and object concreteness, making it possible to work with physical, virtual or mental objects.

Regarding the action axis, the EIFFEL model refers to enacted action when describing physical actions happening in the physical environment, in which the individual is the actor of the activities; to instrumented actions when students perform actions in a virtual environment which involve the manipulation of pictures or symbols but do not require a formal symbolic language (i.e they might use a simplified pictorial placeholder instead of constructing their code) and lastly to formal actions when students perform symbolic actions in a virtual environment. They are the authors of their programs and use a specific syntax to create and modify their programs.

Highly concrete activities (enacted activities) are expected to have a high degree of action-concept congruence to promote understanding. This means the action performed will have a strong and clear association with the concept teachers are looking to explain to their students.

Regarding the object axis, the model refers to physical objects as tangible, 3D objects which individuals can manipulate freely, virtual objects as those set on a computer or tablet screen which individuals manipulate through dragging or tapping with their fingers and lastly mental objects to intangible representations of objects in the physical or virtual world that do not have a 3D or 2D correlate, and in which operations are done through evoking. Figure 2.2 shows the relation between these phases according to their location in the action and object concreteness axis.

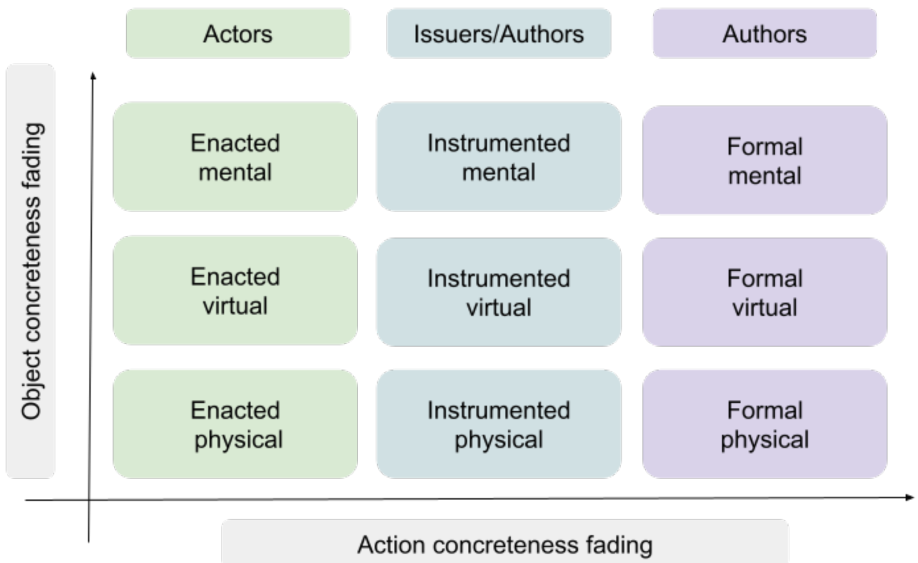


Figure 2.2: Image constructed based on the description of the Eiffel model by Kallia and Cutts (2022).

As children progress through activities in the EIFFEL model, their role in them is expected to change. Three roles were defined in the model:

- Actor: Children represent their programs using themselves as objects
- Issuer: Children learn to give commands to a machine and see the output of their command in a physical or virtual output
- Author: Children use symbolic language to construct their own code and engage in the planning, testing and evaluation of their programs

These roles correspond to the progression of activities, as seen in figure 2.2. This model presents a conceptual progression based on grounded cognition, which accompanies children's development. Part of my aims in the present thesis is to build upon this model in order to encompass more aspects of the learning microsystem, such as instructional practices and teachers' roles in the learning process. Moreover, one of the objectives for this thesis was to evaluate the model's efficacy in supporting students' conceptual development as well as identifying learning trajectories for indicators of conceptual understanding.

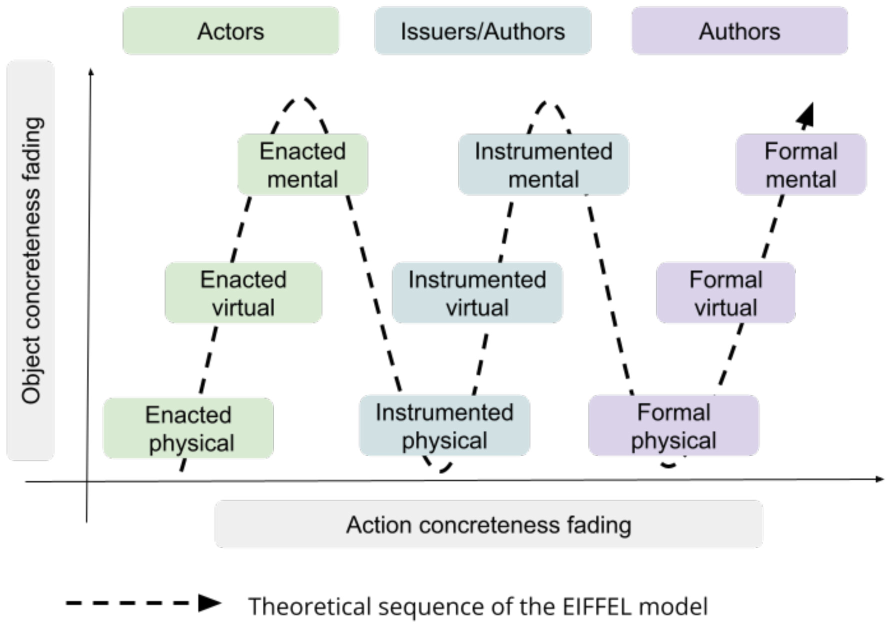


Figure 2.3: Theoretical sequence of the Eiffel model by Kallia and Cutts (2022).

Next, my aim was to draw from an established theory-driven way to structure lessons in order to build upon existing research on the topic. As such, Legitimation Code Theory (LCT) is a sociological theory developed by Karl Maton (Maton, 2013b), focused on the analysis of knowledge-building practices. LCT constitutes an explanatory framework and mode of analysis for the interrelation between theory and practice. Maton proposes several legitimation devices which help define the legitimation codes and how these shape the dynamic social field of evidence. In the words of Maton: “To analyse legitimation codes is thus to explore what is possible for whom, when, where and how, and who is able to define these possibilities, when, where and how” (Maton, 2013a, p. 44).

It is worth noting that Maton’s work is critical of the influence that research on psychology and sociology has had on educational research. Specifically, he considers this research to be overly-focused on learning and thus suffers from what he coined as “knowledge-blindness", the lack of awareness of knowledge itself as an object of study.

Explicitly, he claims: “psychologically-informed approaches typically focus on generic processes of learning and sideline differences between the forms of knowledge being learned. Research on ‘transfer’, for example, explores forms of knowing (‘knowing with’, ‘knowing that’, ‘knowing how’, etc.) rather than knowledge” (Maton, 2013a). Part of this is what distinguishes Maton’s work from constructivist theories, as in the latter, knowledge is seen as constructed within the learner, while Maton proposes that knowledge is not reducible to an individual’s way of knowing, although it emerges from them. Maton’s proposal consists of refocusing our attention on the way power relations affect the experiences of social groups with knowledge and challenges the notion that knowledge-building is merely cumulative. Thus, its focus on knowledge and specifically how content-related aspects of knowledge, such as specificity and complexity, affect teaching makes this a valuable contribution to how theory is brought into practice and will inform the way in which lessons are structured and planned in the present study.

While Maton's theory is extensive and describes a wide range of codes, I will specifically focus on the semantic code as it directly relates to the learning of concepts. In particular, Maton's idea of semantic profile analysis is based on two dimensions: their context-dependency, which Maton calls "semantic gravity" and their complexity, which he refers to as "semantic density". "Semantic waves" are the product of the analysis of lesson activities and specifically signal the movements between simplicity and complexity and between concreteness and abstraction in knowledge. Strong semantic gravity means concepts are highly context-dependent, while weaker semantic gravity means meaning is more abstract; stronger semantic density means concepts are highly complex, while weaker semantic density designates simpler concepts.

How are semantic waves theoretically aligned with the EIFFEL model? Firstly, both have an inherent emphasis on the importance of conceptual (semantic) knowledge for learning. Moreover, in practice, semantic waves make use of fluctuations between concrete experiences and abstract notions in order to promote understanding.

However, these theories have been proposed at different levels: while we often see semantic waves at the lesson-planning level of instruction, the EIFFEL model focuses on utilising different types of action and objects throughout several sessions.

Grounded cognition theory might provide a cognitive explanation for the effectiveness of semantic waves: if we argue that abstract thought is grounded in embodied action and situational experience (Barsalou et al., 2008), children's transit through a semantic wave in a lesson provides different experiences and links abstract and practical knowledge within the lesson. Moreover, the focus on semantic knowledge is also present in the need for conceptual-action congruency described by Kallia and Cutts (2022).

At the lesson planning level, Waite et al. (2019) described semantic waves as a process of signalling (the teacher highlights a new concept is about to be introduced), concept introduction (technical presentation), connecting (linking the concept to a practical activity), practice (execution of a low-density practical activity), counter-expectancy (expanding the concept), and lastly a return to higher levels of abstraction.

Based on these arguments of empirical complementarity, part of this research will integrate the use of semantic waves to instruction using the EIFFEL model.

2.6 Final remarks:

Throughout this chapter, I have presented the main theoretical foundations supporting this research. This work is, fundamentally, an interdisciplinary perspective of computing education that aims to draw from discipline-specific materials as well as literature from diverse fields such as learning sciences, education, psychology and cognitive science (Margulieux et al., 2019; Robins et al., 2019). In this sense, it draws from current research in grounded cognition theory (Barsalou, 2015; Barsalou et al., 2008) in order to empirically build on a novel theoretical framework for promoting children's conceptual understanding designed for early learners of computing (Kallia and Cutts, 2022).

Moreover, it was the aim of this work to have a developmental perspective of conceptual understanding in computing and contribute to bridging the established gaps regarding the understanding of conceptual learning trajectories for foundational computing concepts in early years, as it draws methodologically from mixed methods research (Creswell and Creswell, 2017) and the microgenetic method (Siegler, 2006), in order to both provide a description of the learning trajectories and consider the dynamic aspects of the learning environment (or microsystem in Bronfenbrenner's terms) through an ethnographic approach.

As such, the present work advances our knowledge of these processes by:

a) Identifying current practices in computing education that could be analysed through a grounded cognition perspective

b) Co-designing along with participating teachers, a theory and practice-driven intervention for early years computing classrooms based on the EIFFEL pedagogical model.

c) Identifying behavioural indicators of conceptual understanding in young children through situated classroom observation

d) Empirically evaluating the efficacy of the intervention through both quantitative and qualitative methods

e) Describing young learners' learning trajectories of computing concepts throughout the intervention using a microgenetic approach.

As a result, the current work has several implications. Firstly, it has theoretical implications in contributing to the budding area of research regarding the use of cognitive science knowledge and grounded cognition theory in particular, applied in the service of computing education research.

Secondly, it has empirical implications as it will contribute experimental evidence of the efficacy of the EIFFEL pedagogical framework, which will allow us to identify both strengths and limitations to this approach and further improve it in order to create evidence-based interventions. Moreover, it will have an ecological approach to research by focusing not only on children's processes but also on teachers' perspectives.

Thirdly, it has instructional and practical implications by creating a set of materials that will be available for other teachers who might be interested in applying a similar approach in their classrooms or might find the materials useful for everyday practice, as well as identifying indicators of conceptual understanding that might be useful in the creation of classroom-based observational assessments for early years computing. Lastly, it constitutes a methodological contribution through the application of a microgenetic approach that will contribute to our current understanding of young children's learning trajectories of computing concepts.

Chapter 3

Methodology

This chapter aims to provide a detailed description of the research methods used in this thesis. In addition, it will cover the ontological and epistemological perspectives overarching these studies, as well as their implications in the selection of the research design and methodology. The present research is structured in five phases, including conducting a systematic literature review, using design-based research to iterate over the EIFFEL model for conceptual understanding in computing education, evaluating this intervention through both a qualitative ethnographic approach and a microgenetic, quantitative, and quasi-experimental approach as well as capturing teacher's perspectives on the intervention.

3.1 Ontological and epistemological framework

According to Creswell and Creswell (2017), transparent research designs ought to start by making explicit their underlying philosophical assumptions or "world-views" about reality and knowledge. Ontology has been defined as the "concept or nature of reality" (Creswell, 2021). Closely linked to ontology but at the knowledge-building level is epistemology (i.e., the study of knowledge). Crotty (1998) defined epistemologies as "the theory of knowledge embedded in the theoretical perspective and thereby in the methodology" (Crotty, 1998, p. 3). Other authors have referred to these ways of conceptualising knowledge about the world as "paradigms" (Mertens, 2023; Morgan, 2014) in its original meaning used by Kuhn (1997).

The critical importance of reflection in the ontological and epistemological positions we take as researchers lies in the fact that these world-views permeate our interpretations and stance towards our findings, as well as the methods we choose. Moon and Blackman (2014) point out that most ontological positions can be classified in a spectrum between realism (i.e., the notion that an external reality exists and can be accessed and studied) and relativism (i.e the notion that there is not a single reality but multiple realities that are within the individuals constructing them). At the epistemological level, a realist ontology would align with objectivism, and a relativist ontology with subjectivism (Saliya, 2024; Terry et al., 2017)

Considering different ontological and epistemological frameworks required an analysis of my own beliefs and implications as a researcher, and is undoubtedly embedded within my own cultural experiences with research and the research community I have been surrounded with throughout my academic life. I reflect more on my own positionality regarding research and how my own contextual factors might impact my approach in section 3.1.1. This is especially relevant since the present studies are conducted through a mixed methods approach, including a qualitative perspective that calls for an explicit examination of my own beliefs in order to contextualise its interpretations (Corlett and Mavin, 2018; Sibbald et al., 2024).

My research is framed from the ontological perspective of pragmatism (Bernecker and Pritchard, 2011). This means that I understand reality as inherently dynamic and shaped by human practices and actions, not focusing on the discovery and pursuit of universal truth but on the situated usefulness of ideas and concepts bounded by historical and social contexts. Moreover, I acknowledge the fact that every view of reality is inherently flawed.

The process through which I considered the epistemological and ontological background of my research can not be described as linear: while my approach to the philosophy of science has been a part of my formation as a researcher, the specific considerations explained in the present work are strongly guided by the examination of the research questions and previous works in this specific context. I identify that my background and interest in educational processes have shaped me into pragmatism through the immersion in a highly complex and relational field that is unlikely to be comprehended to the best of my ability by limiting myself to one single method or perspective.

At the philosophical level Misak (2011) explains about pragmatic epistemologies: *(...) truth is not a relationship between our beliefs and the believer-independent world but, rather, is the best we human inquirers could do.*" (Misak, 2011, p.861). Pragmatism proposes to overcome the classical duality between the positivist and constructivist paradigms (Maarouf, 2019) by emphasising the practical consequences of knowledge.

Pragmatist views of research have been influenced by foundational works by philosophers such as Charles Sanders Peirce, William James, and John Dewey (Creswell and Creswell, 2017). The work of Dewey, in particular, is relevant for this work as it highlights an ecological perspective of knowledge (Hammond, 2013) shaped by the interplay of action and its situated experience. Thus, a mixed methods approach (Maarouf, 2019; Molina-Azorin, 2016) is congruent with this view, as this does not limit me as a researcher in the range of applicable methodologies to comprehend a given subject of study.

Some of the tenets of pragmatism include empiricism, naturalism, fallibilism and contextualism (Misak, 2011). Empiricism has its roots in the postulates of philosophers such as David Hume (Hume, 2000, originally published in 1740) or John Locke (Locke, 1959, originally published in 1689) but also psychologist William James, who stated *"True ideas are those that we can assimilate, validate, corroborate and verify"* (James, 1949, p. 20), highlighting the role of experience and testing in knowledge creation. Naturalism in this context highlights the role of working with the reality at hand:

> We are like sailors adrift at sea, never able to return to dry dock to reconstruct our boat out of the finest materials. We work with what we have, replacing our boat of knowledge plank by plank, as required by the surprise of experience. Misak (2011, p.20)

Fallibilism consists of the notion that ideas are constantly subject to revision, therefore stepping away from notions of absolute certainty (Fennell, 2024). Meanwhile, contextualism (Lerner and Benson, 2013; Lerner and Kauffman, 1985) highlights the importance of situating knowledge by taking into account its environmental characteristics. This view also emphasises longitudinal and process-oriented methodologies, which this research utilises and will be discussed further on in this section.

Given the complex nature of the research subject at hand, that is, the learning processes and trajectories taken by young children to comprehend foundational concepts in computing, it was evident that a non-restrictive epistemological stance and methodological toolbox were needed to properly encompass it (Creswell and Creswell, 2017). This focus on problem-solving and interest in real-world settings has led me to consider that taking a pragmatist approach to research improves a researcher's ability to examine the object of study from multiple perspectives. In a recent paper, McDermott et al. (2023) discusses the necessity for a philosophy of computing education and the importance of meta-theories in defining the values of a given field. In their paper, the authors argue that computing education research includes "the philosophy of education, as well as the empirical study of educational topics in the field through the methods of the natural, cognitive, and social sciences" (McDermott et al., 2023, p. 8). In line with this, Tedre and Pajunen (2022) have argued that the pragmatic view is the most suitable for computing education research as it is able to coherently target its plurality regarding their object of study and methodologies.

Moreover, this approach has several overlaps with relational and systemic perspectives of developmental sciences (Lerner and Benson, 2013; Overton, 2010), which have already discussed as part of the theoretical basis for this research in previous sections and build strongly on contextualist epistemic views. Thus, this approach is specifically adequate for the study of probabilistic, multi-level phenomena such as the one at hand (Simpson, 2018) and is the perspective regarded in the present work.

3.1.1 Positionality and reflexivity

To begin this section, I will firstly explain why I chose to include a positionality section in my research. As explained in the previous section, I take a pragmatist epistemological and methodological stand. As such, I am committed to acknowledging and considering the strengths and limitations of several research methods that I expect, combined, will only enrich our understanding of the process of conceptual understanding in computing (the main theme of this work). My contextualist views also make me acknowledge the non-neutrality of the ideas proposed in this and all academic endeavours (Overton, 2010; Overton et al., 2006, 2015). It follows thus that I acknowledge that my identity, experiences and personal values shape my approach to research. I must state, following the ideas proposed by Terry et al. (2017), that I do not view this as a limitation but rather as a strength of this research that will allow future readers to contextualise its findings and support its interpretation, especially in the context of qualitative ethnographic findings where inductive approaches to data analysis are utilised. I consider that establishing my positionality as a researcher will provide transparency to the findings presented and increase reflexivity (Gurr et al., 2024). Moreover, recent works such as those of Secules et al. (2021) have identified researcher's positionality affects not only what questions we ask and what we choose to examine, but also practical aspects of research, such as how we communicate with participants and how we approach fieldwork.

Martin et al. (2022) warns us that writing a positionality statement also includes risks, as the process of engaging in reflexivity brings with it the inherent discomfort of challenging and examining our own core beliefs and possible biases. I have personally felt this resistance while examining some of the demographic, social, cultural and identity-related aspects I have considered in relation to my field of study: I identify as a middle-class, cisgender white woman from Latin America, specifically the relatively small country of Uruguay. I grew up in Uruguay in a middle-income household, and my childhood was marked by one of the country's harshest economic crises in the year 2002. I attended public early childhood and primary education, a fact I consider important because it fostered strong affective ties to the public education system. This experience has entrenched my view that it is necessary for all children to have access to high-quality and innovative learning opportunities.

My personal values put education as one of the top priorities and ways to achieve less inequality and promote a fairer world, as it has the power to bring forward new voices and empower people to promote change in their surroundings. My country's history and cultural background have a strong emphasis on promoting accessibility to public, mandatory and secular education for all children (Varela, 1964). I believe offering educational opportunities early on can help students build identities that shape and transform their realities. Bringing computing science and computational thinking to schools is a relatively new area of knowledge in the Uruguayan context, as such, I believe in its potential to offer students cognitive and practical tools that promote their overall development as well as their learning of the disciplines, sparking new areas of interest for students that might want to pursue a computer science learning trajectory in the future.

Moreover, I acknowledge my gender identity and values regarding my role as a woman in society influence my interest in the research topic as well, as it has been rewarding throughout the process of this research, observing young girls take interest in computing, an area that has been historically, and continues to be, male-dominated (Master et al., 2021; Zdawczyk and Varma, 2023). Despite this, I also acknowledge the privileges encompassed by being a white and educated woman and the fact that there are intersectional struggles I might not have faced based on this fact. Regarding this, my educational background has certainly shaped my views regarding topics that are directly targeted in this research. I can identify that my background in psychology has influenced my interest in education and cognition's role in learning. Previous experiences working with teachers and students in schools have drawn me to conducting applied research and trying to study phenomena on-site. I must also consider my personal views on childhood and children within the context of the fundamental human right to education, as well as children's rights (Oestreich, 1998). I consider children's opinions to be of high value and contextualise their voices within the principles of progressive autonomy and participation, emphasising their agency not just in learning but being as a whole (Tortajada et al., 2022).

In addition to the topics mentioned above, I also acknowledge that the PhD process itself has transformed part of my views regarding research, both by broadening my toolbox as a researcher as well as exposing me to new literature, fields and experiences through academic collaboration and engaging with the participants in the present studies.

In addition, it is important that I mention my positionality in relation to the main topic of this research: conceptual understanding in computing science. While I have covered part of my interest in education, it is also important that I acknowledge my approach to the discipline. While I am not a computer scientist, I view the topic as intrinsically interdisciplinary. My first university degree was in psychology, mainly from a cognitive and developmental perspective, and my master's degree was in cognitive science, where I studied the effects of an educational robotics intervention on children's computational thinking skills. As such, this experience drew me near to my current topic, but it was during my PhD that I discovered new interests in conceptual knowledge in computing and what these meant in the context of the discipline. Paradoxically, I consider myself both an outsider and insider in the context of this research; I am an outsider to the discipline of computing science as well as to the participating institutions' educational context, yet I am an insider in the fact that I have had some experience in working with young children, performing interviews, building rapport and implementing an educational intervention.

To finalise this section, it is my objective that this positionality statement clarifies the point of view from which I approach my research and aids others in understanding and interpreting its results. Throughout the research process, I remained committed to ongoing reflexivity, recognising that my presence and interpretation during observation are not neutral. As such, the presentation of qualitative results in this work abandons claims of objectivity and aims for transparency in its interpretation. In order to mitigate possible biases, I, along with my supervisor, engaged in peer debriefing discussions throughout the entire process. With this statement, I hope to provide context for the reader and to contribute to a more ethical and reflective research practice.

3.2 Research design

In line with the ontological and epistemic approach presented in the previous section of this work, my research design implements a convergent mixed methods approach. The research was divided into five phases or studies:

- Phase 1 consisted of conducting a systematic review of literature in order to identify previous practices in teaching computing using activities based on grounded cognition or unplugged methods.

- Phase 2 used design-based research to capitalise on the findings from my systematic literature review and the expertise of teachers from real-world classroom settings to expand and refine the conceptual model used to teach computing to young children.

- Phase 3-A takes a qualitative perspective in order to examine within-classroom and situated aspects of the learning process. The objective of this study was to identify indicators of conceptual understanding. To achieve this, I used an ethnographic approach which encompassed participant observation, post-session interviews with students and teachers, and field notes. This corpus of data was analysed through reflexive thematic analysis.

- Phase 3-B uses quantitative methods to explore the efficacy of my teaching and learning model in the ecology of the computing classroom. In order to do this, I followed the structure of a quasi-experimental approach and also implemented a longitudinal-microgenetic approach, which allowed me to have a developmental perspective on children's progress throughout the intervention. I used pre and post-test assessments in children's computational thinking skills and analysed their conceptual understanding throughout the intervention.

- Lastly, Phase 3-C makes use of in-depth interviews in order to acquire teachers' impressions, experiences and feedback on the implementation of the intervention based on the EIFFEL model through a qualitative perspective.

Figure 3.1 presents a flowchart of the different phases of this research.

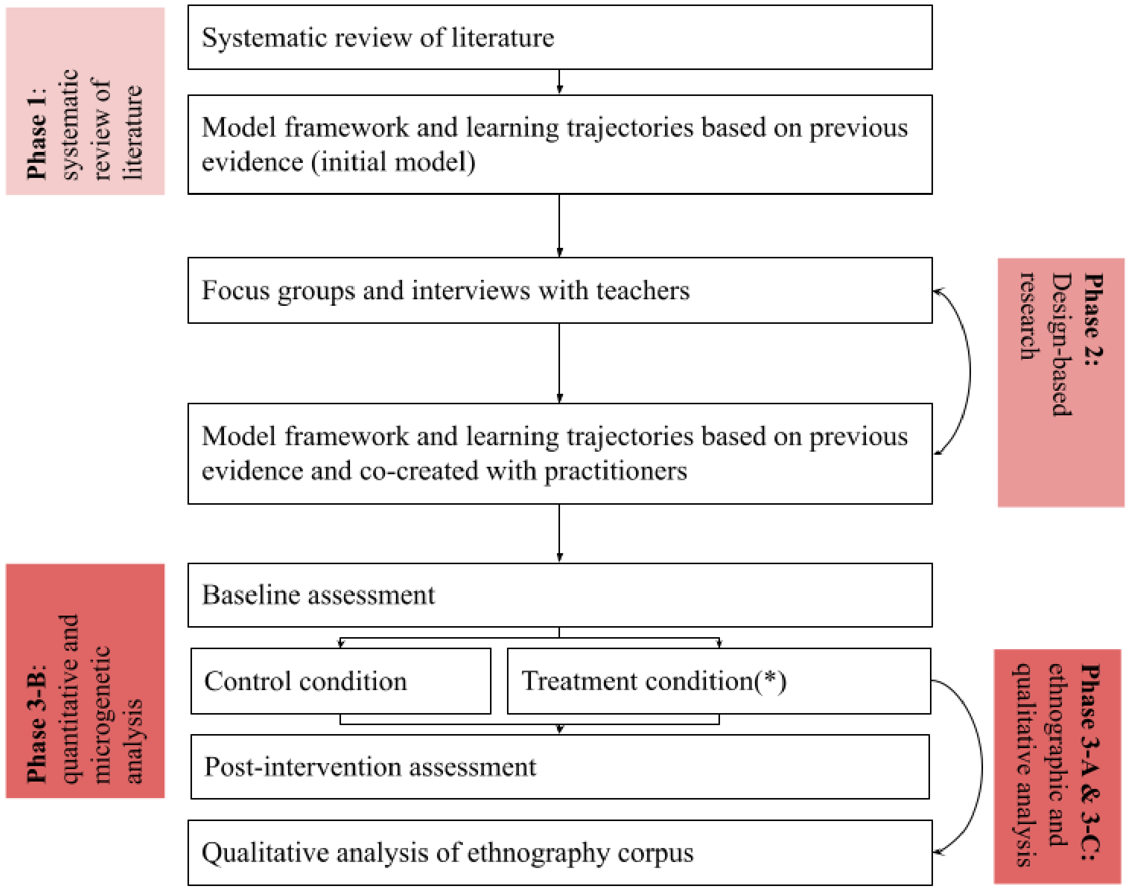


Figure 3.1: Flowchart presenting the methodological structure of this thesis. (*) Indicates between-session assessments in line with the microgenetic method and classroom ethnography which are presented further in section 3.3.5.

3.3 Methods

3.3.1 Phase 1: Systematic review of literature

My first study in the context of this thesis consisted of a systematic review of literature with the objective of identifying previous research on action-based and grounded approaches for early years computer science education.

A systematic literature review examines the evidence on a specific set of questions through the use of clear methods and is useful in synthesising existing knowledge (Boell and Cecez-Kecmanovic, 2015; Borrego et al., 2014).

My review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and recommendations (Page et al., 2021). The PRISMA guidelines present a flowchart and 27-item checklist which establishes the screening and data collection process for articles (Page et al., 2021; Selçuk, 2019).

A section of these results was presented at the 18th WiPSCE Conference on Primary and Secondary Computing Education Research and published as a research paper (Gerosa et al., 2023). The present section expands on the findings reported in this publication by introducing further elements of analysis and interpretation of these results.

The main objective of conducting a systematic review of literature was to identify successful practices for grounded cognition in CS education for young learners (early childhood and primary education) and analyse their characteristics. To achieve this, the following research questions were defined:

1. What kind of grounded approaches have yielded positive results in CS education for young learners?
2. Which theoretical background informs this research?
3. What were the outcomes of these approaches?
4. Which technological tools were used?
5. What are the implications for designing activities in the early years of computing based on grounded cognition?

Search strategy

An automated search was conducted in order to find relevant studies. The search included terms based on grounded cognition theory, computing education, and filters with the targeted age-range (early childhood and primary). After obtaining a primary list of studies, manual data extraction was conducted.

I selected articles that included terms in their abstracts and were published between 2006 and 2023. I opted to use the year 2006 as a starting point, given that this was the year of Jeanette Wing's influential paper on computational thinking (Wing, 2006), which sparked interest in the field. In addition, previous studies have identified an increase in the number of publications that coincides with this milestone (Haseski et al., 2018). The specific search strings used are presented in appendix A.1.1.

In addition to focusing the search to grounded cognition theory, I also included neighbouring terms such as "unplugged" in order to include those utilising concrete objects for teaching.

Four databases were utilised in the search: these include ACM Digital Library, IEEE, ERIC and Scopus. The final number of articles included per database was 16 for ACM Digital Library, 14 for Scopus, 4 for IEEE, and 3 for ERIC. A total of 8 articles were included in the review through backward snowballing (Jalali and Wohlin, 2012).

Inclusion criteria

In a systematic literature review, researchers ought to establish a set of inclusion criteria for the examined publications. These include the specific characteristics and conditions all articles selected for review must meet to be included in the study and are defined beforehand in order to delineate the field (Creswell and Creswell, 2017). The inclusion criteria established for this study were as follows:

1. Participants are children attending early years or primary school (4 to 12 years of age)
2. Participants take part in computer science or computational thinking learning activities
3. Empirical studies published in peer-reviewed journals or conferences
4. Sample is neurotypical
5. Publication year between 2006 and 2022

Analysis procedure

Firstly, I conducted a screening of abstracts of the relevant studies and recorded whether they fulfilled inclusion criteria 1-3. Studies that met all 3 criteria were selected for full-text review. My supervisor checked the fulfilment of the inclusion criteria in a random sub-sample of 20% of the abstracts. Later on, results were discussed until agreement was met.

During the full-text review, we rechecked that the selected articles met the inclusion criteria and moved on to selecting studies for further analysis and data extraction. I applied backwards snowballing (Jalali and Wohlin, 2012; Kitchenham et al., 2015) in order to assess the inclusion of relevant publications cited in the initial set of papers.

After full text review, several variables of interest were extracted. These included: targeted computing concepts, age span of participants, instruction duration, type and description of computing activity, sample size, theoretical background, technology, outcome variables and main results of the studies.

To analyse the activities, an inductive approach was implemented. This means that the categories utilised in the context of this study emerged from the analysis of the available data (Thomas, 2006). In order to achieve a consensus on which articles were to be included for analysis, my supervisor analysed a random sub-sample composed of 20% of the studies that met the criteria, and together we discussed the established criteria and classifications. Once a total consensus was reached, I proceeded to code the remainder of the sample.

For studies' outcomes, categories were defined a priori, following previous work by Su and Yang (2023) on systematic report of computing activities. Three categories were defined:

- Learning outcome, where the study focuses on assessing conceptual learning

- Cognitive outcome, where the study focuses on assessing gains on a specific cognitive skill
- Motivational outcome, where the study focuses on students' self-efficacy, self-reported motivation or enjoyment during tasks

Despite the conceptual distinction made above, it is worth considering that in practice, learning, cognition and motivation are necessarily interconnected. However, this distinction was considered relevant as the focus of these assessments was fundamentally different: while learning outcomes focused primarily on conceptual knowledge, cognitive outcomes focused more on general-domain skills that do not require previous content knowledge, such as problem-solving or reasoning. Lastly, motivational outcomes focused on affective aspects related to computing, such as task enjoyment or self-efficacy. The results from this particular phase of research are presented in section 4.1.

3.3.2 Phase 2: Model refinement and creation of pedagogical materials for the intervention

Following phase 1, my objective was to draw from its empirical findings as well as real-world classroom settings in order to improve the theoretical model. The main research question guiding this study was:

- How can we design a set of activities based on grounded cognition to promote conceptual understanding in computing?

The research question guiding this section builds on the conceptual work started by Kallia and Cutts (2022). Based on this initial model, I implemented a design-based research methodology in order to create instructional materials that were useful for conducting an educational intervention aimed at promoting conceptual understanding based on grounded cognition. Design-based research (DBR) is often used in educational research in the building and testing of instructional design practices (Anderson and Shattuck, 2012).

According to McKenney and Reeves (2018), educational research must be fundamentally theoretically oriented, interventionist in nature, collaborative, iterative and responsively grounded in participants' expertise. Following these principles, they proposed a general model for designing educational interventions that involves three main phases: analysis and exploration, design and construction, and lastly evaluation and reflection (McKenney and Reeves, 2018). Figure 3.2 represents McKenney and Reeves (2018)'s model.

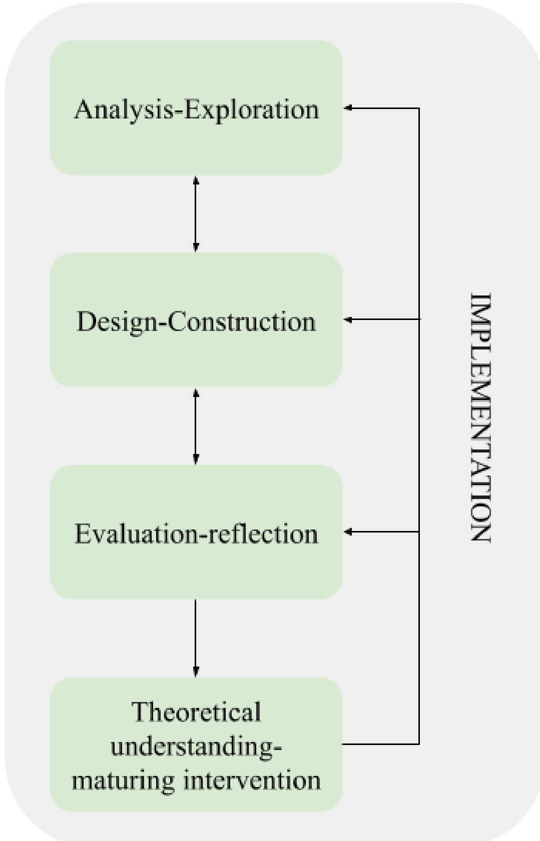


Figure 3.2: Model for designing educational interventions. Adapted from McKenney and Reeves (2018).

The first includes the process of diagnosis and is empirical in nature; it involves the familiarisation with the design setting. The design and construction phase is defined by the authors as theoretically oriented and described as similar to the construction of a conceptual model. This aligns with our current phase of research. As stated, given the iterative nature of design-based research, it can be considered that while the objective of phase 2 in our study was creating an intervention with practice-oriented educational materials as the "final" product, it is part of a larger iterative cycle comprising all five phases of this thesis. Thus, lastly, the evaluation-reflection stage is empirical in nature and involves, within this phase of our study, contrasting our intervention with teachers' perspectives through semi-structured interviews and discussion sessions.

One of the strengths of DBR is its aim of bridging the gaps between research and practice by being rooted in real-world settings. Educational design-based research is interested in what Bronfenbrenner (1977) referred to as ecological validity, meaning ensuring, in this case, through an iterative and informed process that the researchers' assumptions about the topic are aligned, useful for, and informed by the participants. In this view, teacher participants are not passive recipients of the intervention but active co-constructors of it.

DBR involves a cyclical process of design, implementation, evaluation, and refinement (Kelly et al., 2008). There are significant discussions about the role of theory and practice in the design-based research process; however, as pointed out by Bannan-Ritland and Baek (2014), there is consensus among researchers that theoretical propositions are crucial in the design of educational innovations. These authors based their contributions on the Integrative Learning Design Framework (ILDF), a theoretical framework which structures the establishment of research-based design problems and establishes a set of coherent steps with which to proceed using this methodology. According to Bannan-Ritland and Baek (2014), design-based research consists of a four-phase structure composed of informed exploration, enactment, and evaluation of local and broad impacts. Phase 2 of this research covers the first of these four phases: informed exploration, with the pilot study conducted, consisting of an exploratory phase evaluation and reflection, and lastly, my empirical study completes the cycle of design.

During informed exploration, theoretical contributions are taken into consideration to establish the gaps in the theory and the existing benchmarks. In the context of this research, this process is linked directly with the critical analysis of our phase one results. Thus, my design process involved the following steps: a) considering our results from phase one and identifying theoretical gaps in our existing learning model, b) creating a first conceptual expansion of the model based on the literature, specifically by including specific metacognitive prompts and structuring the lessons through semantic waves c) empirically validating this model with practitioners through the use of expert interviews and focus groups in order to iteratively gain feedback on our model.

One of the strengths of DBR is that it enhances the feasibility of application of our model by ensuring its practical relevance through collaboration with practitioners. Fostering collaborative partnerships between researchers and practitioners is vital for the success of any educational enterprise (Barab and Squire, 2016; Collins et al., 2016; Joseph, 2004).

Two participating teachers were involved in the co-creation of the model throughout every stage, while one teacher participated only in the pilot phase. In the following section, I will describe the actions taken for the design of the intervention through the lens of McKenney and Reeves (2018)'s model.

For the analysis and exploration phase, the authors include the process of problem identification and diagnosis (McKenney and Reeves, 2018), as such, this phase is directly linked to the results from the study examining the relevant literature in action-based activities for computing education, as described in section 3.3.1. This phase allowed us to identify relevant issues in reporting and gaps in the literature regarding the theoretical background of the revised studies. Results from this phase are presented in section 4.1.

The main product resulting from this phase in my study is theoretical: it allowed me to establish a set of goals for the materials in order to satisfy criteria in line with previous research, as well as pointed to possible pitfalls or gaps to make up for. The main product guiding the design and construction phase is the creation of the supporting materials and activities provided for teachers in order to implement the EIFFEL (Kallia and Cutts, 2022) model.

In order to create these, I designed an initial document following the objectives established in phase 2 and including a set of instructional adaptations as presented in the theoretical background. The materials were designed with the aim of being practice-oriented and easy to implement, while also incorporating instructional guidelines and the key theoretical ideas behind the model. Several iterations of the activities were created and revised before engaging in the co-design phase. It is worth noting that while the original draft of the materials was created in English, given that participants' native language is Spanish, translated materials were created for teachers to engage with during the co-design process in order to obtain their feedback. As such, two sets of equivalent translations were ultimately produced in the context of this thesis, which could be used in both English and Spanish-speaking contexts.

Pilot study

For the evaluation and exploration phase, I include two separate phases, one consisting of the implementation of a pilot study in which only the activities targeting the concept of sequences were implemented in a separate classroom in order to have a small-scale exploration of the intervention.

In total, 5 activities targeting the concept of sequences were implemented during the pilot phase. A class of ten 5 year old children (6 boys, 4 girls) took part on these activities during the span of three weeks. The objective of conducting a pilot was to assess the feasibility and appropriateness of the planned activities and assessment tools, and, as in the later study, all participants provided informed consent and were informed of the objectives of the study prior to their participation.

In this context, observations and informal feedback were used to identify any logistical challenges, clarify instructions, and refine the materials. In addition, I was able to test and improve on some of the interview protocols for children that would later be used during the formal evaluation.

After the considerations from the pilot study were taken into account, the document with activities was later revised by the two participating teachers who would fully participate in the co-design process of the activities. A 1 and a half hour discussion session was held with the teachers in which I used a semi-structured interview protocol in order to inquire about their previous experiences with computing education, their practices, and gather their feedback regarding the activities. Afterwards, any comments or suggestions were included in the final version of the activities.

I conducted participant observation throughout the implementation of the activities and interviewed the teacher afterwards in order to gather feedback on this stage. Based on the results of this stage, adjustments were made to the activities as presented in section 4.2.

Lastly, a controlled evaluation of the intervention was held in study 3 of this research, in which immersion, detailed registration and quantitative microgenetic following was conducted. These methods are expanded on in the following sections. Figure 3.3 presents a summary of this process.

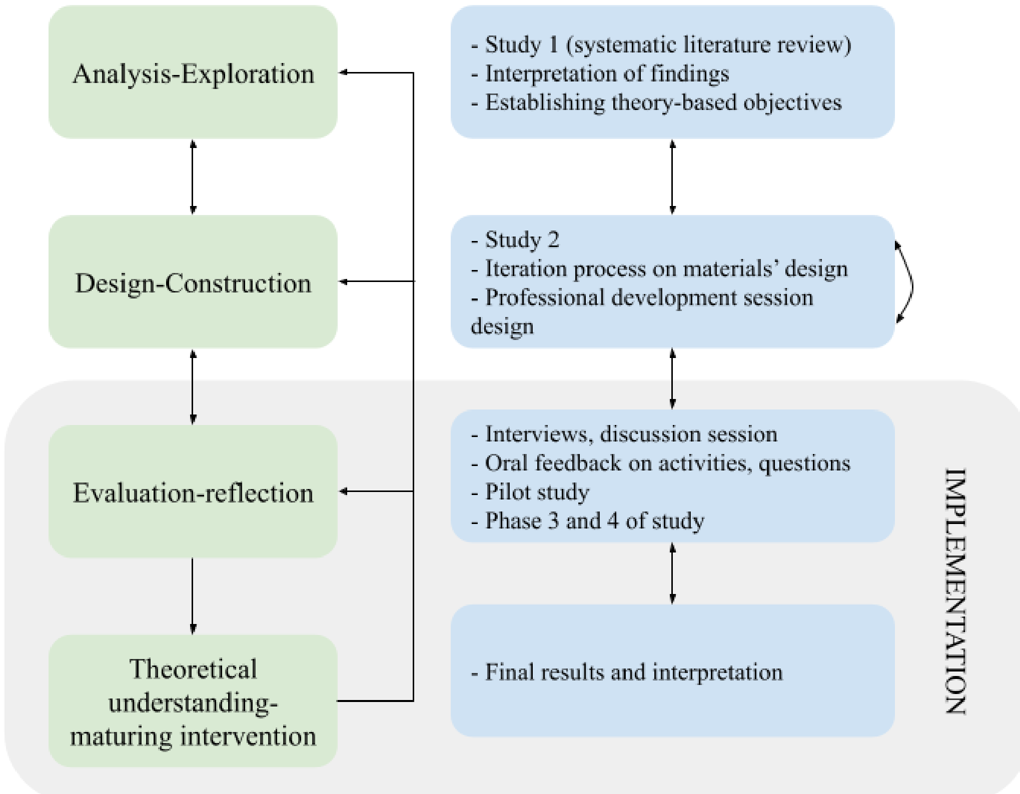


Figure 3.3: Actions in the present study (blue) based on McKenney and Reeves (2018)'s model (green)

3.3.3 Phase 3-A: Identifying indicators of conceptual understanding through classroom ethnography

Classroom ethnography

In this section, I present the methodological considerations for part A of study 3. This study was exploratory and ethnographic, and the main research question it tried to answer was:

- Can we identify behavioural indicators of understanding in computing?

In order to answer this question, I employed an ethnographic approach in order to capture the complexities of the classroom and obtain highly situated data from the implementation. Ethnography has its roots as a research method in the social and cultural studies, particularly in the field of anthropology (Erickson, 2010; Naidoo, 2012; Walford, 2018). Recently, it has seen increasing use in educational research (Green and Bloome, 2004; Maeder, 2018; Pole and Morrison, 2003).

Etymologically, ethnography comes from the Greek "ethnos" meaning tribe or people and "grapho" meaning writing or description. Thus, ethnography uses systematic descriptions of people and culture through participant observation and interviews (Harrison, 2014). The main objective of the researcher during ethnography is to be immersed in the daily culture and practices of their field of study. This includes the study and systematisation of cultural values, group dynamics, behaviours and social interactions in their context. Ethnographic research needs to identify key aspects of the observed dynamic, which includes highlighting key actors, events and processes as well as considering my own implication as a researcher (Creswell and Creswell, 2017). Throughout its history, ethnography has not escaped tensions between positivist and interpretative paradigms of knowledge-building (Harrison, 2014). The first formal ethnographic studies, which are now referred to as classic or realist ethnography, were conducted by researchers in the XIX century, such as Bronislaw Malinowski, an Austro-Hungarian researcher who studied native cultures in the Trobriand Islands of Papua New Guinea (Roldán, 2013).

Classic ethnography has its roots in the positivist and post-positivist paradigm, where researchers employed detailed descriptions of their environments that were presented as fact, with the ethnographer usually creating a third-person narration of the events and considering themselves as an outside viewer intricately examining a foreign group's cultural practices (Erickson, 2010, 2011). Later on, critical ethnography would challenge this notion and move towards an interpretative framework by pointing out the problems with the idea of objective observation. Rather than on factual description, critical ethnography focuses on capturing the subjective points of view of the people being observed, the different power struggles and dynamics between social groups and considering ethnography as an agent for change within the communities and culture it studies (Erickson, 2010; Gordon et al., 2001; Palmer and Caldas, 2015).

When applied to the field of education, ethnography has the particularity that classrooms are not an unknown or strange subject, since most of us have at some point in our lives been part of a classroom dynamic (Erickson, 2010). Thus, classroom ethnography strays from the classical anthropological paradigm of observing the exotic to focus on a familiar environment.

This makes the methodological aspects of ethnographic research even more relevant. As pointed out by Erickson (2010, p. 322), the role of the ethnographer in the context of classrooms is: "to make the familiar strange" in order to capture both the explicit and implicit dynamics within it. Some authors have pointed out that identifying the ideas surrounding knowledge and how knowledge is achieved and cultivated is especially relevant in educational ethnography (Gordon et al., 2001), a topic which is central to this thesis, which focuses on students' conceptual understanding.

However, it is worth pointing out that not all observations could be considered ethnographic in nature, and thus it is important to define their methodological characteristics. Erickson (2010) has presented a set of tenets of classroom ethnography which will be followed in our observation. In the context of this research, this include: a) Long-term observation, which will be spanning several weeks in order to be immersed in the habits of the classroom; b) contextualisation of the setting, meaning understanding the relational systems between students and the teacher; c) understanding the different social roles within the classrooms and how it affects learning; d) identifying relevant micro-cultural practices within the classroom and finally e) identifying how both students and teachers signify the computing learning process and create meaning around their practices.

The present ethnography made use of two main methodological tools: participant observation and interviews.

Participant observation consists of "establishing a place in some natural setting on a relatively long-term basis in order to investigate, experience and represent the social life and social processes that occur in that setting" (Emerson et al., 2001, p. 352) and makes use of thorough fieldnotes (annotations of occurrences in the observation).

Meanwhile, interviews consist of a discourse organisation-form based on questions and answers. The word interview is derived from the French root *entrevoir*, meaning "to see one another". Interviews are used in a wide range of areas such as journalism, clinical settings, the workforce and of course, research (Roulston, 2011). Heyl (2001) has pointed out that interviews in the context of ethnographic research should be self-aware of the co-construction of meaning during the process, thus acknowledging the interviewer's role as well as that of the person being interviewed.

As previously mentioned, critical ethnography has rejected the presumption of objectivity of classical ethnography to focus on capturing the worldviews and subjectivities of what is observed. Moreover, it no longer sees the observer as a neutral outsider but embraces its implication in the observation. According to Heyl (2001), this has led some researchers to dismiss ethnography as a non-rigorous methodology. However, its deep focus on understanding the contextual aspects of a problem is a strength of ethnography rather than a weakness. Especially in educational settings, it provides us with a way to represent the situatedness of the learning process and capture the intricacies of a complex environment (Nixon and Odoyo, 2020).

Lastly, participant observation and thorough fieldwork notes were taken throughout the sessions in line with the ethnographic method.

Participants for phase 3

The studied groups who participated in the intervention consisted of two classrooms and their respective teachers. Classroom A is a first-grade class comprising 16 children (12 boys, 4 girls) aged 6 to 7, while classroom B has 7 children aged 5 to 6 (4 boys, 3 girls). Thus, two teachers and twenty-three children participated in the intervention. For phase 3-B, a different class participated as a passive control group, continuing their activities as usual. This group (classroom C) was a first-grade class of 6 children (3 boys, 3 girls) making the total sample for phase 3-B, twenty-nine children.

The sample size utilised in these studies is methodologically in line with previous ethnographic studies in computing education and aligns with the objectives of these methods, as the aim of ethnographic and microgenetic research is to create an in-depth understanding and contextualised interpretation of social processes and repeated observations for each participant are prioritised (Chinn and Sherin, 2014; Hammersley and Atkinson, 2019; Pole and Morrison, 2003; Siegler, 2006).

As such, ethnography values prolonged engagement, description and iterative analysis (Nixon and Odoyo, 2020). Moreover, the microgenetic method used throughout multiple sessions further strengthens the analytical strategy by creating several observations per participant. As such, the qualitative data presented in this section includes ethnographic records for each session in each class as well as post-session interviews from each participating child throughout all ten sessions (figure 4.11), creating an extensive dataset for qualitative analysis.

In phase 3-B of the study, I utilised inferential statistics within the mixed methods framework of this thesis. The objective of this was to compare results from the groups applying the intervention using the EIFFEL framework developed in phase 2 of this research, with a control group of 6 children. Given this reduced number of participants, between-subject effects should be considered exploratory (Creswell, 2021; Creswell and Creswell, 2017). Thus, although the sample size is modest in the quantitative sense (Collins et al., 2007), this is appropriate for the study's aims, as increasing participant numbers at the expense of analytical depth might have undermined the intensive fieldwork and microgenetic analysis that are central to achieving the study's objectives (Lavelli et al., 2005).

3.3.4 Programming tools utilised in the context of these studies:

In this section, I will provide context regarding the specific tools utilised in phase 3 of this research in order to make their features and programming capabilities transparent, as well as their possible limitations. It is worth mentioning at this point that the selection of the tools was done based on their flexibility to be incorporated into activities for the EIFFEL (Kallia and Cutts, 2022) framework, the previous evidence of their suitability for work in early years and first years of primary education context and their availability in the education centre at the moment of the implementation:

- **Beebot:** Beebot is a tangible floor robot designed for young learners. Its design allows users to input commands using a button interface located at the top of its structure. This robot allows the following movement capabilities: forward, backwards, turn right 90 degrees, and turn left 90 degrees, enabling the device to move across a grid in 15 cm increments. It is equipped with memory capacity, which allows children to improve their programming sequences incrementally or start over by using the "clear" button. In recent models of this tool, its memory capacity has been reported as up to 200 commands (Jaanuska and Meister, 2025). Even though this robot does not have a specific built-in way to create repetitions or conditionals, these have been previously introduced through activity design (Bakala et al., 2022; Papadakis and Kalogiannakis, 2022; Seckel et al., 2023). Figure 3.4 represents the interface of Beebot along with its main functions.

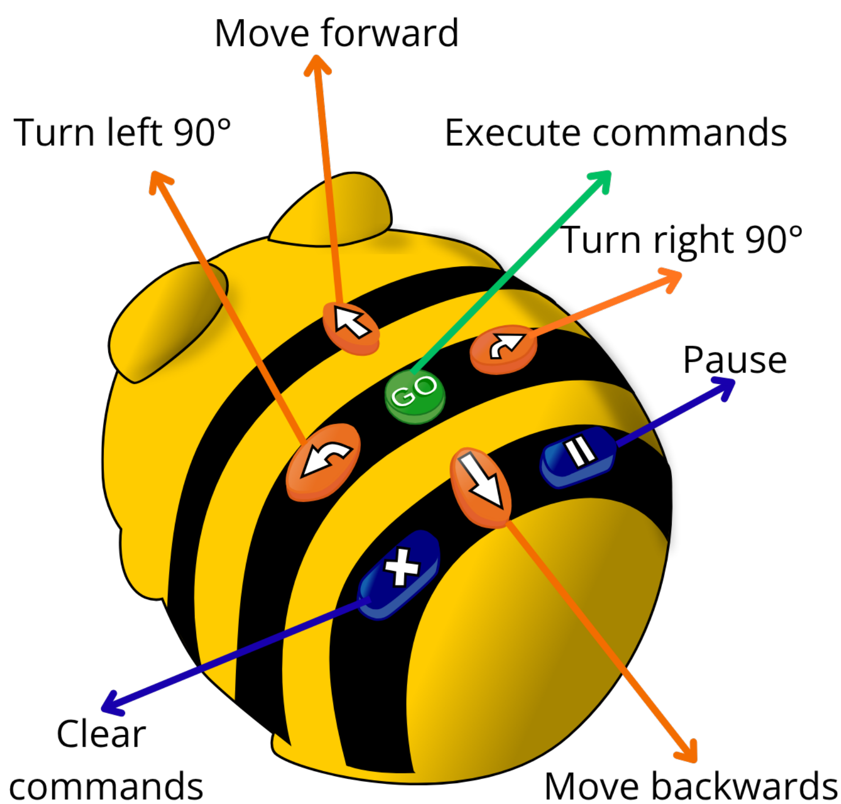


Figure 3.4: Beebot interface. Adapted from Seckel et al. (2023).

- **ScratchJr:** ScratchJr is a visual block-based programming environment designed for children who are in the process of consolidating their reading and writing skills. It was designed as a developmentally appropriate precursor of the Scratch programming environment by incorporating pictorial commands. ScratchJr is available as a free application and is able to be downloaded to touch-screen digital devices such as cellphones or tablets.

In the context of this research, ScratchJr was implemented using touch-screen tablets, presenting a drag and drop interface. Its interface is composed of a programming zone in which children construct their programs, a "character" zone in which children select the character or object being programmed at a given time, a "stage" zone where characters or objects execute the commands and lastly a "page" zone in which they are able to switch between different pages in their story. Command sequences are implemented through horizontal lines of stacked blocks, visually connected as puzzle pieces. In addition, different types of blocks are distinguishable through differing colours (motion blocks are blue, sound blocks are green, control blocks are orange, triggering blocks are yellow, look personalisation blocks are purple, and lastly end blocks are red. An example of its user interface can be seen in Figure 3.5. ScratchJr supports the construction of sequences by allowing students to program step-by-step instructions including different blocks, for example as seen in Figure 3.5 in which multiple movement blocks are implemented. Repetition can be achieved through a specific loop block (as seen on the figure below) as well as the "repeat forever" block. Finally, while it does not provide a specific block for conditional statements, conditional logic can be partly implemented through events triggered by conditions (for example, "if character is tapped, then move") or the use of messages.

Figure 3.5: ScratchJr programming interface. Image authored by Tufts University, Scratch Foundation obtained via CC BY-SA 4.0.

Procedure for phase 3-A

Participant observation was conducted over a period of three months during which 12 computing lessons (each lasting approximately 1 hour) were imparted to two early childhood classrooms. Part of the ethnographic process involved acclimating and exploring the environment as well as building rapport with participants. In order to ensure this and have sufficient time to conduct post-session interviews with each child (phase 3 of the study), I spent about 2 and a half hours per session per class in the field (approximately 60 hours in total), which included time for activities, interviews and a brief recess. In addition, a 2-hour professional development session was held with teachers before the start of the intervention, as well as a 1-hour discussion session in which they provided feedback regarding the activities in the model.

Field notes were recorded after each lesson and comprised both descriptions and personal reflections of observed interactions between the teacher and children or amongst the children. The observation conducted aimed to record children's behaviour and interaction dynamics within the classroom amongst themselves, with their teacher and in the context of each of the activities being proposed. As such, I registered their affect and excitement, their comments about the activity, and any relevant exchanges regarding the activity, as well as those that were relevant in any problem-solving behaviour.

Moreover, I focused on how group dynamics affected the development of the activity, observing their attention and willingness to participate as well as their disengagement. The teachers participated in a two-hour professional development session during which they were introduced to the activities of the intervention and the objectives of the application of the EIFFEL model to promote conceptual understanding in young children, as well as some aspects of grounded cognition theory, the use of meta- cognitive prompts and guidelines on the structure of each lesson.

Before the activities, participating teachers were able to ask questions and make suggestions if they felt they needed to adjust the activities to better fit the characteristics of their classroom. For example, teacher A requested one of the activities, which was suggested for small groups be held in pairs to promote behavioural management; however, overall, no major changes were made to the activity set that modified its objectives or structure. In addition to participant observation, semi-structured interviews were conducted with the teachers after the intervention in order to capture their perspectives on the implementation of the model. The interview guide was flexible and adapted to allow participants to express their thoughts freely while also covering key themes related to the research questions. Interviews for teachers lasted between 20 and 40 minutes and were audio-recorded and transcribed verbatim.

To further explore children's understanding and triangulate the information recorded during the observation, shorter individual interviews were conducted with the children after each activity. Particularly, the interviews were aimed at exploring their understanding of the activity as well as the concept underlying it. All participants were interviewed after each activity. To do this, children were asked to recount the activity briefly using their own words and were prompted to explain what they understood by the target concept. The post-session interview protocol for children is presented in Appendix A.3.2.

Qualitative data analysis

The ethnographic data stemming from field note observations and interviews were transcribed and analysed through thematic analysis. Field notes were descriptive and reflective and were taken throughout the study to document the observers' understanding of the research context and interactions with participants to maintain transparency. In addition, interviews with participants were audio-recorded and transcribed after each session. While observational data and field notes served as the primary source for our ethnographic analysis, post-session interviews were thematically coded in order to analyse the frequency of the identified themes using a microgenetic design.

As stated in the previous section, the philosophical stance for this research is rooted in contextualism. Thus, my data analysis followed an inductive approach. This means that each code and theme identified in the analysis was constructed using a bottom-up approach (Boyatzis, 1998; Fereday and Muir-Cochrane, 2006). Braun and Clarke (2021) point out that inductive thematic analysis is data-driven in the sense that coding and theme development are directed by the content of the data itself. The procedure followed the guidelines established by these authors: firstly, I conducted initial readings of the data in order to familiarise myself with the material. Since interview transcriptions were previously done, some level of familiarisation with the material had already been achieved. However, during this phase, I tried to immerse myself in the content, taking a whole-intervention perspective and identifying significant incidents or recurring patterns in the data that might be significant for the analysis. Data familiarisation was conducted iteratively by doing several read-throughs of transcriptions and field notes.

After I had familiarised myself with the material, I began to generate initial codes. Each transcript was examined line by line, with relevant sections of the text being highlighted using colour schemes as initial themes started to emerge. The coding at this stage was semantic in nature, meaning that the content of the code was closely related to the content of the text. As stated by Braun and Clarke (2021): *"Semantic codes capture explicitly-expressed meaning; they often stay close to the language of participants or the overt meanings of data"* (Braun and Clarke, 2021, p. 101).

One of the key aspects of thematic analysis is that it allows for flexibility in the construction of meaning around the dataset. Other epistemological perspectives, such as positivistic views, might consider the reflective side of thematic analysis as a threat to validity or objectivity. Contrary to this, Braun and Clarke (2021) highlights the role of the researcher's positionality and reflectivity in the process of analysis. The authors argue that thematic analysis can not be understood as a passive extraction of themes from the data, but as a process of creating meaning.

As such, my own perspectives were not treated as an aspect to be controlled but as a tool in the analysis. In order to contrast the themes found, I implemented peer debriefing strategies (Creswell and Creswell, 2017) with my supervisor, who engaged in extensive discussion of the data, offering insights and reflections on the relevance of the identified themes.

Following this inductive process, a total of nine semantic codes were utilised in the analysis of children's explanations of the activities; these are further presented in the results for this study. Following this analysis, I used the microgenetic approach in order to explore not just the presence or the semantic meaning of the codes extracted from our dataset, but also their frequency and trajectories throughout the sessions.

Observing change: Microgenetic methods

The microgenetic methods has its origins in developmental cognitive psychology (Brock and Taber, 2017; Luwel, 2012) as an approach capable of capturing the process of change throughout development. Microgenetic studies are a type of longitudinal study, as it implements several observations of the subjects over time, with the particularity that observations are performed with a frequency higher than the one expected for the studied process (Flynn et al., 2006; Flynn and Siegler, 2007; Siegler, 2006). This characteristic is what allows microgenetic studies to capture the process of change in a given skill or learning.

Microgenetic studies have their origins in the works of Werner (Werner, 1957) and Vygotsky (Vygotsky and Cole, 1978), two authors interested in the genesis and development of cognition. Thus, this method is especially relevant in the learning sciences and educational contexts as it is able to account for complex processes which might be non-linear in nature (Brock and Taber, 2017).

A typical microgenetic study involves multiple, frequent assessments of a given domain and the analysis of its trajectory, and therefore, it is a specifically pertinent method to understand children's process of acquiring understanding of computing concepts. Siegler (2006) proposed microgenetic methods are able to account for elements which are not captured in traditional cross-sectional or even longitudinal studies, such as the path, rate, variability between-subjects and breadth (generalisability) of change. Current studies use this design in conjunction with multilevel non-linear modelling of the collected data (Cheshire et al., 2007; Van der Ven et al., 2012) in order to capture these characteristics. Figure 3.6 presents a summary of the intervention. It is worth noting that although the intervention lasted 12 sessions in total, only 10 were analysed quantitatively, as one consisted of an introductory session and one consisted of an exploratory session in order for children to be familiarised with ScratchJr as a tool. As such, ten sessions are considered in the analysis.

A few studies have employed the microgenetic approach to examine learning processes in computing or using a computer-supported environment. For example, Kuhn et al. (2008) reported on 28 sixth graders' argumentative discourse activity in a computer-supported environment. Dickes et al. (2016) used the microgenetic approach to examine elementary students' programming in the context of science classes. Meanwhile, Vogler et al. (2013) analysed students' literacy through the microgenetic observation of online classroom discussions obtained through video data. In their study, Sullivan et al. (2015), focused on developing microgenetic learning analytics from student's problem solving strategies using robots. Despite these emergent results, thus far, none of the previous studies employed the microgenetic approach in order to explore the emergence of conceptual understanding in young children.

In the present study, I analysed children's conceptual understanding indicators after each computing session through the coding of a semi-structured interview as explained in the previous section. For the microgenetic approach, I analysed the mean frequency of appearance of each of the established semantic codes for the entire group of participating children, as my interest in this section was to examine the existence of developmental trajectories at this stage. One of the strengths of the microgenetic approach is that it focuses on capturing change throughout sessions and thus allows us to identify when each of the observed behaviours begins, as well as their trajectories throughout the intervention.

3.3.5 Phase 3-B: Quantitative and sequential evaluation of the intervention

Quasi-experimental design

As stated in section 3.2, the structure of a quasi-experimental design was used to evaluate the efficacy of the activities. This structure was also complemented with the use of longitudinal-microgenetic assessments in order account for progression and obtain developmental and learning trajectories of children's process.

A total of 3 classrooms (N=29) participated in the study. One of these was used as a control condition in order to compare groups quantitatively. The control condition consisted of a passive control, meaning that they continued their activities as usual without any intervention.

The following assessments were implemented for students:

- Beginners' computational thinking test (Zapata-Cáceres et al., 2020): the beginners' computational thinking test (BCTt) is a computational thinking test designed for children aged 5 to 12 years. It assesses children's performance in 6 programming structures: sequences, simple loops, nested loops, if-then conditionals, if-then-else conditionals and while loops, drawing theoretically from computational thinking models such as Brennan and Resnick (2012). Taking into account the concepts targeted in the present intervention, items referring to if-then-else statements and while-loops were omitted, as these concepts would not be covered in the proposed activities. This assessment was used both before and after the intervention in order to capture any changes related to the intervention. This instrument builds on prior work by Román-González et al. (2017) for teenagers by creating an adaptation specifically designed for younger children. This test was selected specifically because it targeted several of the concepts of interest of this study and allowed for a more objective assessment.

- BRIEF-P questionnaire for executive function Gioia et al. (2016): BRIEF-P is a 63-item questionnaire designed to be filled out by parents assessing their children's executive function through their everyday behaviours. The questionnaire is composed of 6 factors, which include inhibition, flexibility, emotional control, working memory and planning. This assessment was implemented once, at pre-test, in order to account for children's executive function skills as a control variable for our intervention. This questionnaire was completed by each student's parents.

- Language test of temporal concepts (ECTE): Language skills will be controlled through the assessment of children's knowledge of temporal concepts. The ECTE test (Fitipalde, 2021) is composed of 10 temporal sequences and is designed for children aged 4-6 and explores children's ability to logically organise a temporal sequence involving a character represented in pictures, as well as their understanding of the concepts of *before*, *after*, *first* and *last*. This assessment was used once, at pre-test, as a control variable. This assessment builds on previous work by Purpura et al. (2019, 2017) regarding children's use of spatial concepts. An example of an item for this test can be found in Appendix A.3.5

In addition to the pre-test and post-test assessments implemented in the quasi-experimental design, I assessed conceptual understanding with a microgenetic design through exploring the frequency of behaviours defined by the indicators of conceptual understanding. This will allow us to have a developmental, trajectory-based perspective of children's learning. These are explained below:

- Conceptual understanding indicators: As described in the methodology for phase 3-A of this research, my approach to assessing conceptual understanding after each session consisted of the application of post-session semi-structured interviews, in which children were asked to briefly recount the activity and prompted to provide, in their own words, a definition of the concept. Each interview lasted between 5 and 10 minutes. The interview protocol for this assessment is presented in Appendix A.3.2. Thus, the conceptual understanding indicators for the microgenetic analysis of post-session interviews are directly related to the results obtained in study 3-A through thematic analysis.

- Procedural assessment: An assessment rubric was created in order to register children's performance during each of the activities. The rubric is presented in appendix A.3.4.

- Enjoyment and difficulty indicators: In order to assess students' enjoyment of each activity and how difficult they perceived each task, two questions were included in my interview protocol that inquired about these elements. A 5-point Likert scale was utilised for these dimensions, seen in Appendix A.3.2.

Procedure for phase 3-B

Classrooms were randomly assigned to either the treatment condition (support of their learning CS through the EIFFEL model activity set, two classrooms) or the control condition (continuing their activities as usual without any intervention, one classroom). Both teacher and student measures were taken, with teacher elements of assessment being described in the following section (3-C). After assigning each group to their condition and completing the professional development and interviews conducted with teachers in phase 2, a total of 12 computing sessions using the EIFFEL instructional model designed were implemented. A flowchart describing each of the assessments implemented at each phase of the study can be seen in Figure 3.6.

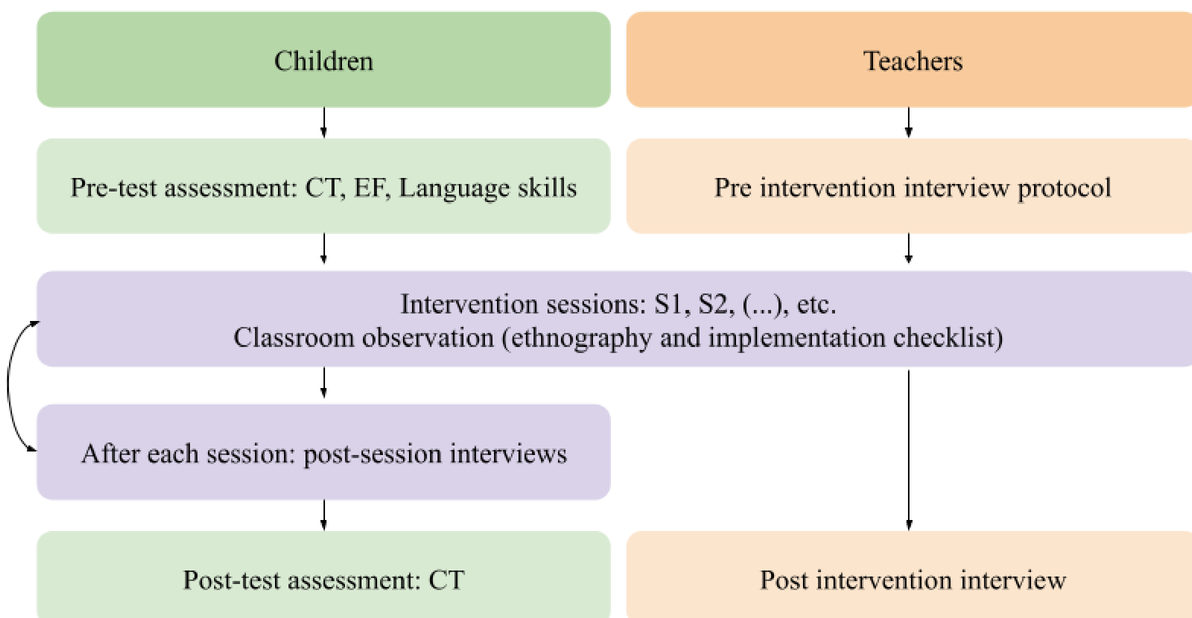


Figure 3.6: Phase 3 diagram

Data analysis

A repeated measures analysis of variance (RM-ANOVA) was conducted using the ezANOVA function (Lawrence, 2016) from the ez package in R (R Core Team, 2024) to assess the

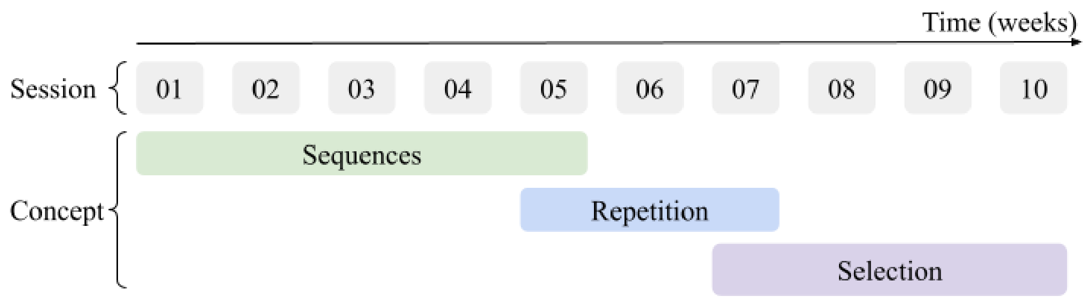


Figure 3.7: Session diagram for intervention.

effect of time (within-subjects factor) and group (between-subjects factor) on the children's total score on the beginners' computational thinking test (Zapata-Cáceres et al., 2020). The within-subjects factor (time) had two levels (baseline and follow-up), and the between-subjects factor (group) represented each quasi-experimental condition (treatment vs control). A random factor of the subject was included in order to account for the repeated observations.

Before conducting the RM-ANOVA, the statistical assumptions to run the model were checked. These included observing the normality of residuals, which were tested through the Shapiro-Wilk test and the homogeneity of variance across groups, which was checked using Levene's test.

For the microgenetic observations, descriptive statistics are calculated on the basis of the frequency of behaviours through time. A within-subject approach is taken for these observations. Qualitative analysis of trajectories was implemented to examine the emergence of behaviours linked to understanding as well as individual variability.

3.3.6 Phase 3-C: Teacher's perspective on the intervention

Lastly, the objective of phase 3-C was to qualitatively evaluate teachers' overall experience implementing the activities, gaining their insight into the process. In order to achieve this, I implemented in-depth post-intervention semi-structured interviews with both participants, generating an area of trust and rapport in order for them to provide feedback. In addition, a classroom observation checklist was used in order to assess the fidelity between the actions taken by teachers during the implementation and the set of activities as co-designed in phase 2 of this thesis.

- Interviews: An in-depth semi-structured interview was held with teachers before and after the intervention in order to explore their background, interest and self-efficacy in computing education. The teacher interview protocol is presented in Appendix A.3.1

– Classroom observation: An ad-hoc classroom checklist was created for the purposes of assessing the fidelity of the implementation according to the guidelines established by the model. The protocol aims to assess three moments in the activity (introduction, development and closing time) as well as the emphasis on the targeted concepts and was used as a way to validate intervention fidelity, which is available in Appendix A.3.3.

3.4 Limitations

In this section, I will critically consider the main methodological limitations of the methods employed in this thesis. Firstly, as stated above, this thesis takes a mixed-methods approach (Creswell, 2021), by integrating the use of design-based research, ethnographic observation, in-depth semi-structured interviews, a quasi-experimental assessment of the intervention and a microgenetic analysis of indicators for conceptual understanding across sessions.

As readers can attest, a broad scope of methodological strategies was implemented. This was considered necessary, as part of the objectives of this thesis is to comprehend young children's conceptual understanding of computing concepts situated in the context of early childhood and primary education. As such, in order to tackle such a complex problem with a variety of elements to be analysed, a mixed-methods approach provided benefits in terms of being able to study different elements of the intervention. Despite this, all research methods have inherent limitations and contrasting views that reflect the diversity of epistemological and ontological paradigms existing in research.

As explained in my positionality and ontological perspective section, this research takes a pragmatist view of research, and thus, I will try to consider different epistemological points of view when reflecting on the limitations of my selected methodology.

From a positivistic perspective, it can be argued that highly context-sensitive qualitative research methods, such as those employed in design-based research, interviews and ethnography, fail to create generalisable knowledge. However, contrasting interpretative views of research consider this to be a strength of these methodologies, as they allow for rich characterisation of environments and in-depth analysis (Braun and Clarke, 2021). Thus, it is worth remembering that the objective of these methodologies is not to create generalisations but to design and comprehend highly contextualised, situated interventions.

For design-based research, this method has been widely used in computing education settings and is one of the key ways in which researchers have tailored their interventions with valuable input from practitioners (Collins et al., 2016; Lo, 2021).

For classroom ethnography, some authors have argued that it is difficult for researchers to build rapport with participants, and thus their presence in the field while conducting observation might have an impact on participants' behaviour, thus affecting the results (Pole and Morrison, 2003). This is a valid concern when considering ethnographic research, as undoubtedly, teachers might feel self-conscious of their teaching practices, or my presence might create minor disruption in a classroom of small children. To mitigate the sensation of being observed by an outsider, an introductory session during the first activity was held in order to build rapport with participants and try to minimise any discomfort. Moreover, sufficient time has been allotted throughout the intervention in order to allow participants grow more confident with their interactions with me as a researcher. It is also worth mentioning that my role as a researcher was always made explicit to the young participants by explaining my role in a developmentally appropriate language.

For my quantitative phase of study, the largest limitation is probably the relatively small sample size, which makes statistical analysis more difficult, as it might increase the possibility of false negatives (Creswell and Creswell, 2017; Mertens, 2023). To mitigate this, robust, simple methods of analysis were utilised rather than more complex, multi-level techniques for analysis that might be more susceptible to small variations in data. For example, I limited the number of factors in my ANOVA to fit the analysis of my main research question in this phase of study. Despite this, all model assumptions for ANOVA were assessed and met, and non-parametric analyses were utilised if needed.

For my microgenetic analysis of conceptual understanding indicators, one possible limitation is that these results are sequentially linked to the findings in section 3-A. Thus, limitations encountered in study 3-A could have implications for my microgenetic study. Moreover, since this part of the study focuses on creating conceptual development trajectories of young children, indicators were grouped across participants in order to create a group-level trajectory. Thus, in accordance to microgenetic tradition (Luwel, 2012; Van der Ven et al., 2012), these results should be interpreted as contextualised to the specific activities conducted in the context of this thesis, as it is possible that different computing activities might elicit different verbal and behavioural cues in children or exhibit different trajectories. Clearly, this has implications for generalisability, but also includes the trade-off of the benefit of creating an in-depth understanding of their trajectories for this context.

My last phase, study 3-C is based on the qualitative analysis of in-depth interviews of the participating teachers. One of its main limitations consists in the fact that only two teachers were able to take part in the full intervention. Thus, one possible concern is that the resulting data might be influenced by teachers' recall and subjective interpretations of their experiences or some aspects of social desirability. As stated above, efforts were made in order for teachers to feel comfortable and create a safe environment to share any opinion they wished to. Moreover, the data analysis for this qualitative phase is inherently interpretative in nature (Braun and Clarke, 2021), an element which was mitigated by including large portions of verbatim quotes in order to contribute to the reader's analysis of my results and increase transparency.

Taken together, these methodological choices reflect deliberate trade-offs that privilege contextual richness, process-level analysis, and real-world applicability, while necessarily circumscribing claims regarding generalisability and direct-causality. Moreover, the methodological choices prioritise a developmental approach, emphasising learning processes above results.

3.5 Methodological summary and analytical procedure

Given that this thesis is comprised of many phases, the objective of this section is to summarise the methodological steps and analytical procedures undertaken. In order to do this, a summary figure was designed to facilitate comprehension of the overall methodological and analytical actions undertaken. In figure 3.8, black arrows represent serial actions.

Action / Phase it contributed to	Phase 1	Phase 2	Phase 3-A	Phase 3-B	Phase 3-C
Systematic review of literature	Procedure Analysis	Analysis			
Theory-driven design		Activity design			
Pilot study takeaways		Activity design and adjustments	Feasibility of observations	Testing of assessments	
Pre-test teacher interview					
Co-design sessions with teachers, feedback session					
Milestone: Set of activities / Intervention design					
Pre-test assessments of CT, language and executive function				Quantitative assessment for children	
Intervention study			**Milestone: Activities are implemented in classrooms**		
Ethnographic observation, field notes			Ethnographic account, identification of indicators of conceptual understanding		
Post-session interviews with children			Identification of indicators of conceptual understanding (thematic analysis)	Microgenetic analysis of frequency of indicators from 3-A, analysis of enjoyment and difficulty of activities	
Post-intervention assessment of CT				Quantitative assessment of intervention	
Milestone: Intervention completed					
Analysis of relation between CT, language and executive function				Correlational Analysis	
Frequency analysis of indicators of conceptual understanding, per session				Trajectories of conceptual understanding and learner profiles	
Post-intervention interviews with teachers					Qualitative analysis of teacher feedback from intervention

Quasi-experimental design

Figure 3.8: Summary of methodological and analytical actions undertaken.

Chapter 4

Results

4.1 Phase 1: Systematic review of literature: are principles of grounded cognition reflected in previous research?

The first result in the context of this systematic literature review is to present a categorisation of the activities and approaches implemented in the analysed studies in order to teach computing to young learners. With these categories in mind, I will provide an analysis of their relation to grounded cognition, specifying whether this approach is implemented. As stated during the methodological section of this phase of study, I considered grounded approaches as all activities that included either the use of concrete, tangible materials to represent information or the use of enactment or embodiment during the activities.

When examining these activities, I was able to identify four categories emerging from this analysis. The identified categories include: unplugged activities, physical computing activities, virtual programming, and mixed approaches. I will provide a brief explanation of each category next.

Computing science unplugged encompasses a set of activities for the learning of computer science concepts and principles which do not require the use of computers. Bell and Vahrenhold (2018), proponents of CS unplugged, define lack of use of computers and programming, sense of play and exploration, being highly kinaesthetic, a constructivist approach, short and simple explanations and a sense of story as key elements in the use of unplugged activities in computing (Bell and Vahrenhold, 2018).

Despite the precision in their definition, the unplugged activities reported in the studies analysed for this review were varied. In order to have a more granular analysis of these empirical studies, subcategories were created to further explain these results.

Three subcategories were used in order to analyse the activities. These included: a) Using concrete objects or toys, b) Using board games with specific rules intrinsic to the gameplay, and c) Paper-based activities solvable through worksheets such as mazes or reasoning activities.

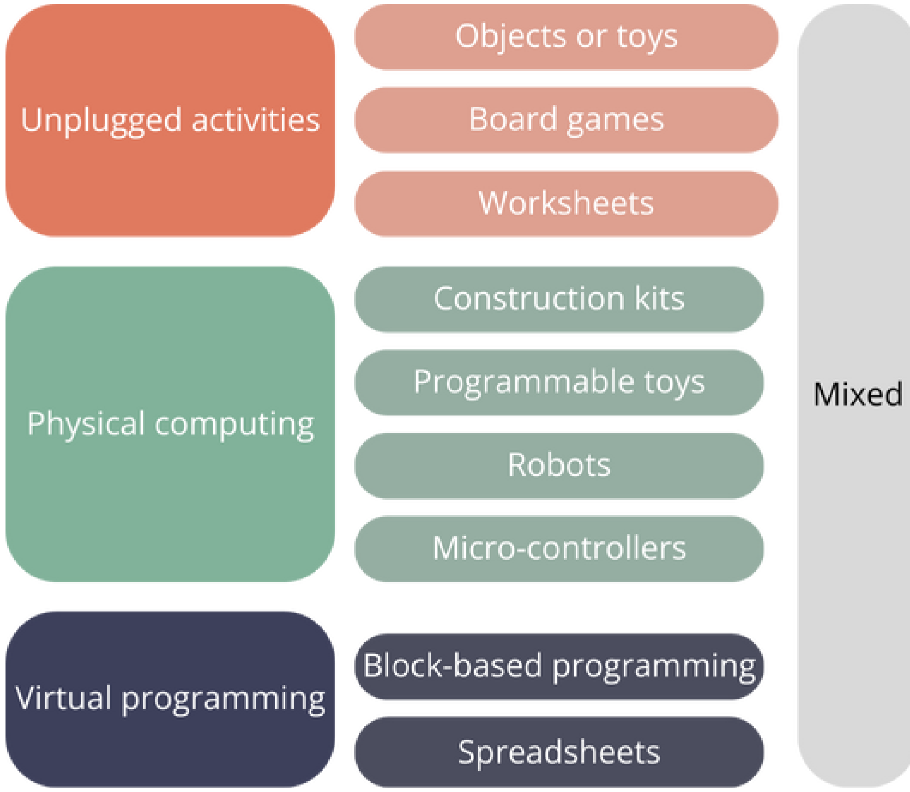


Figure 4.1: Types of activities reported

The results showed 20% (n=9) of the examined articles implemented unplugged activities, composed of 7% (n=3) of the total using objects or toys, 2% (n=1) board games and 11% (n=5) using worksheets.

Physical computing activities can be defined as those involving programmable, tangible computing devices. 24% (n=11) of the examined articles implemented these types of activities. Often, these tools are equipped with sensors and actuators which allow them to interact with their environment through different means which include movement, sound and light.

The subcategories obtained for these activities include: a) physical computing through robots (of which most implement spatial movement as its most salient output), b) Construction kits (for example CyberPLAYce in the work of (Soleimani et al., 2016), where children first read a story and then compose it using the action cards in the construction kit), c) programmable toys and d) microcontrollers. Some examples of activities in this category include the work of Bers et al. (2022a) using programmable robots like Kibo, Faber et al. (2019) using Cubetto, or Luo et al. (2020) with Dash, all of which implemented activities involving the creation of algorithms to get the robot to perform an action. Examples of microcontrollers include the work of Cabrera et al. (2019). The distribution of the studies using physical computing includes 7% (n=3) using construction kits, 2% (n=1) using programmable toys, 14% (n=6) using robots and 2% (n=1) using microcontrollers.

Lastly, I referred to virtual programming as those activities which asked children to program using a graphical interface, such as a computer or tablet. This category is characterised by activities which are screen-based, and thus the representation of objects is subject to the virtual world. 17% (n=8) of the articles implemented solely virtual activities. These are composed of 15% (n=7) block-based programming environments and 2% (n=1) in the use of spreadsheets.

Despite the search being focused on empirical evidence which implemented a grounded approach to the teaching of CS, several articles implemented virtual programming activities, such as Rose et al. (2020), which compared students' performance in programming concepts through comparing Scratch, Pirate Plunder and spreadsheets, or Weintrop et al. (2018) who used Laplaya, a block-based programming environment similar to Scratch.

Lastly, some of the reviewed studies implemented what I categorised as a mixed approach. In mixed approaches to computing activities, these incorporated two or more of the types of activities described above. These were the largest group of studies (33%, n=15) and all possible combinations were reported. Specific examples of these are portrayed in Table 4.1. To name a few, Storjak et al. (2020) started with students using worksheets to plan their algorithms and then using the robots Thymio and Codey Rocky to implement them. Meanwhile, Tsarava et al. (2019) proposed a progression which incorporated all three types of activities by starting with introducing CT concepts through board games and then programming a robot's movement through a graphical interface in Scratch.

Two studies were excluded from this particular analysis, as they presented a general framework and did not provide a sufficiently detailed description of the activities implemented. Table 4.1 presents the classification of the examined studies per type of activity.

Table 4.1: Summary of Activities, adapted from Gerosa et al. (2023)

Type of activity	Studies
Objects or Toys	Città et al. (2019); Ehsan and Cardella (2017); Torres-Torres et al. (2019)
Board games	Tsarava et al. (2018)
Worksheets	Brackmann et al. (2017); Bryndova and Malivsuu (2020); Franklin et al. (2020); Oomori et al. (2019); Pérez-Marín et al. (2018)
Construction kits	Li et al. (2021); Soleimani et al. (2016); Stupurienė et al. (2021)
Programmable toys	Jormanainen and Tukiainen (2020)
Floor robots	Almjally et al. (2020); Angeli and Valanides (2020); Bers et al. (2022a); Faber et al. (2019); Hassenfeld et al. (2020); Luo et al. (2020)
Micro-controllers	Cabrera et al. (2019)
Block-based programming	Minamide et al. (2020); Papadakis et al. (2016); Pinto-Llorente et al. (2016); Rose et al. (2020); Sung et al. (2017); Weintrop et al. (2018); Wong and Cheung (2020)
Spreadsheets	Rose et al. (2020)
Mixed approaches	del Olmo-Muñoz et al. (2020); Dwyer et al. (2014); Francis et al. (2016); Gane et al. (2021); Gardeli and Vosinakis (2019); Hermans and Aivaloglou (2017); Jiang and Wong (2022); Leifheit et al. (2018); Minamide et al. (2020); Ntourou et al. (2021); Saxena et al. (2020); Storjak et al. (2020); Swidan and Hermans (2017); Tran (2019); Tsarava et al. (2019)

One important aspect to explore regarding the characteristics of the employed activities consists of its duration and frequency. Figure 4.2 presents the reported overall duration of the activities measured in hours. It is worth noting that a total of 19 studies either did not report the length of the activities conducted or reported it in a way in which the overall length of time could not be deduced (for example, indicating the activities took part in 8 sessions but lacking a description as to the duration of each session).

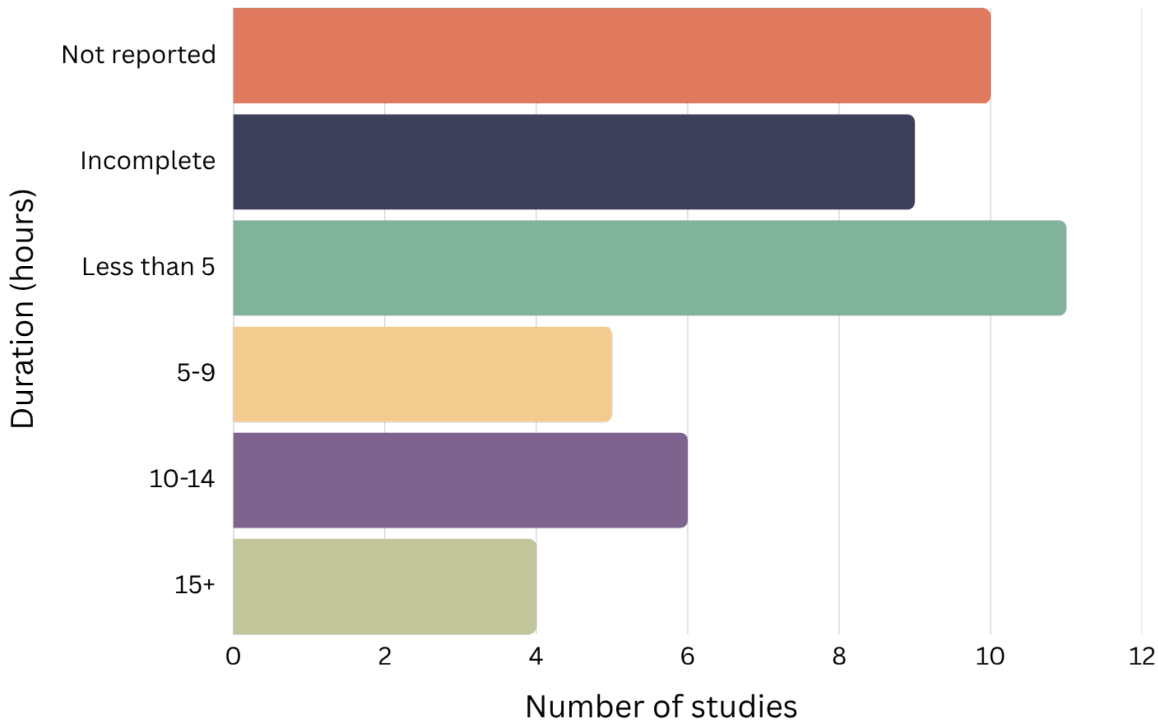


Figure 4.2: Reported duration of activities

Another objective of this systematic review was to analyse the theoretical background cited as supporting this research, as well as its implications for the design of computing activities targeted to young learners.

This next question involved identifying the theoretical backgrounds informing the selected studies. It was surprising to find that, despite the initial search being targeted towards grounded cognition literature, I found only a minority of articles explicitly cited this set of theories as the theoretical background informing their practices. In fact, we found 22 of the reviewed articles did not explicitly state a specific theory of learning as being especially relevant to their design.

Figure 4.3 shows the frequency of the main theoretical backgrounds cited by researchers. These include constructivism, mainly inspired by the works of Piaget (Piaget, 1967) and cited by Dwyer et al. (2014); Jiang and Wong (2022); Leifheit et al. (2018); Li et al. (2021); Luo et al. (2020); Papadakis et al. (2016); Saxena et al. (2020); Stupurienė et al. (2021); Swidan and Hermans (2017) but also the work of Bruner (Bruner, 1966) in Francis et al. (2016).

The constructivist theories of learning posit that knowledge is formed by the interaction and integration of previous experience with the world and new knowledge. According to authors, constructivist pedagogies link to instructional design through practices such as discovery learning, active learning or cognitive apprenticeships (Karagiorgi and Symeou, 2005). As to studies which specifically mentioned being informed by the grounded cognition literature (including embodied, embedded, enacted and extended cognition), these included Almjally et al. (2020);

Città et al. (2019); Francis et al. (2016); Jiang and Wong (2022); Leifheit et al. (2018); Soleimani et al. (2016); Sung et al. (2017); Tsarava et al. (2019). The implications of embodied cognition on instructional design have been linked to conceptual learning through action-concept congruencies (Lindgren and Johnson-Glenberg, 2013), which has led to interventions focused on bodily actions, gestures and manipulatives.

Lastly, several studies cited the constructionist theory of Seymour Papert (Papert, 1980), specifically Bers et al. (2022a); Dwyer et al. (2014); Hassenfeld et al. (2020); Leifheit et al. (2018); Tsarava et al. (2018); Wong and Cheung (2020). Constructionism is a pedagogy derived from and intrinsically linked to constructivism. Similarly, learning by doing, hands-on learning, and learning through constructive play are some of the applications of constructivist theories in the classroom (Ostashewski et al., 2011).

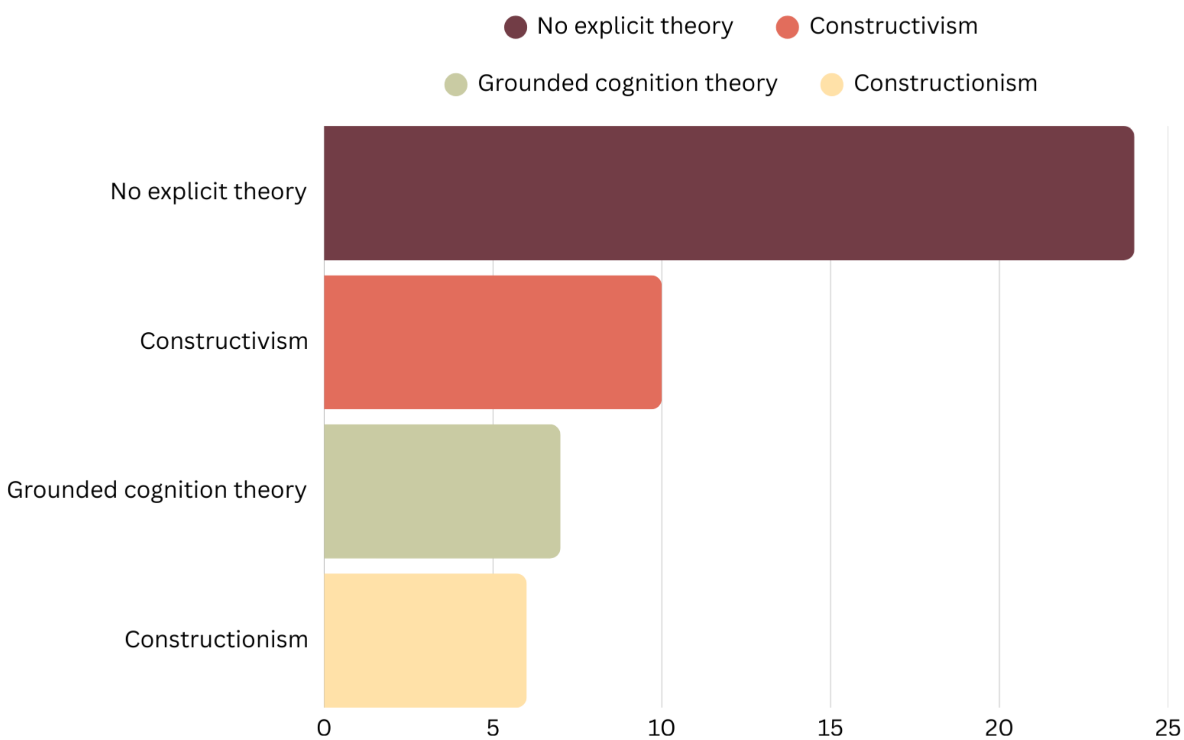


Figure 4.3: Most frequent theoretical backgrounds

As it can be observed, the theoretical frameworks presented by authors were not mutually exclusive; on the contrary, several works were not only informed by more than one theory but by similar frameworks which could be considered as being in a continuum (Ertmer and Newby, 1993). Holton (2010) argued for the supplementary nature of these perspectives. Proulx (2008) suggested enactivism in particular could be seen as an extension of constructivism in the sense that they share a strong common basis in the idea that knowledge stems from the interaction between our previous ideas and new information stemming from our environment. According to Holton (2010) "enactivism and embodied cognition research provide a theoretical grounding as well as a more solid, concrete, empirical foundation for some of the concepts to come out of cognitive science and constructivism", Other theories informing the examined research include experiential learning (Tran, 2019), flow theory (Williams et al., 2015), framing of knowledge (Franklin et al., 2020) and total physical response theory (Saxena et al., 2020).

In Figure 4.4, I present the methodological approaches used in the studies analysed, displaying an even mix of quantitative, qualitative and mixed-methods approaches to research.

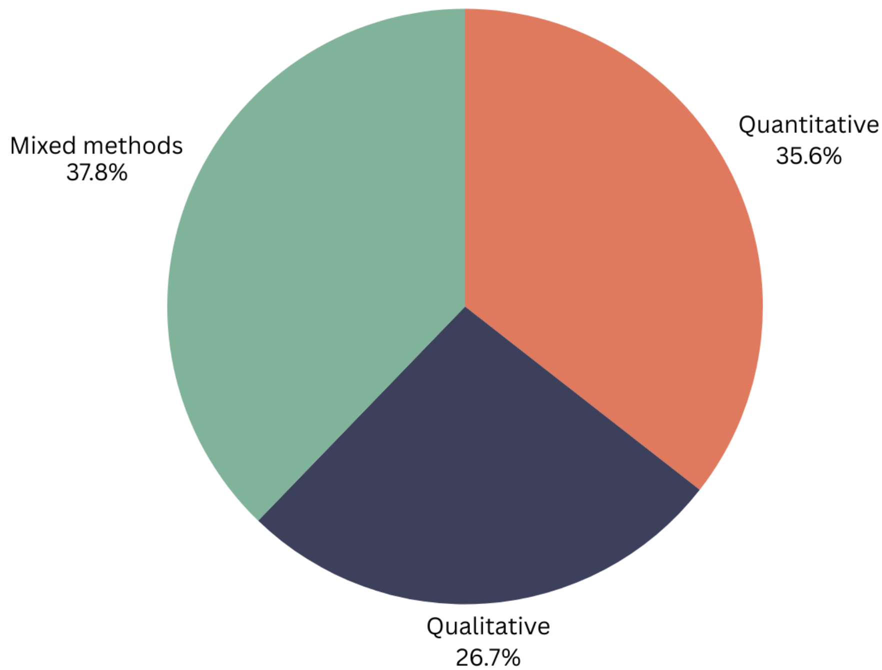


Figure 4.4: Type of studies per methodological approach in this review

Next, I analysed how aspects of grounded cognition might have impacted activity design. Specifically, these include the use of whole-body movement, using concrete materials, implementing concreteness fading in their instructional sequence, and gesture analysis.

All 45 studies were analysed; however, data were extracted from 44, as one study, Picado-Arce et al. (2021), did not include information on the characteristics of the activities implemented. Of the remaining studies, it was found that the most frequent of these practices was the use of concrete materials, which was incorporated in 80% (n=35) of the studies.

The incorporation of student activities which require whole-body movements was present less frequently in 20% (n=9) of the studies (Bers et al., 2022a; Città et al., 2019; del Olmo-Muñoz et al., 2020; Ehsan and Cardella, 2017; Hassenfeld et al., 2020; Hermans and Aivaloglou, 2017; Saxena et al., 2020; Sung et al., 2017; Torres-Torres et al., 2019)).

For example, Città et al. (2019) implemented an activity called "Robot-Tino Walk" in which they asked students to embody a robot and follow specific instructions in a large grid, while Bers et al. (2022a) asked children to program a robot in order to perform a dance which children had previously performed and experienced themselves. Only a minority of the studies incor-

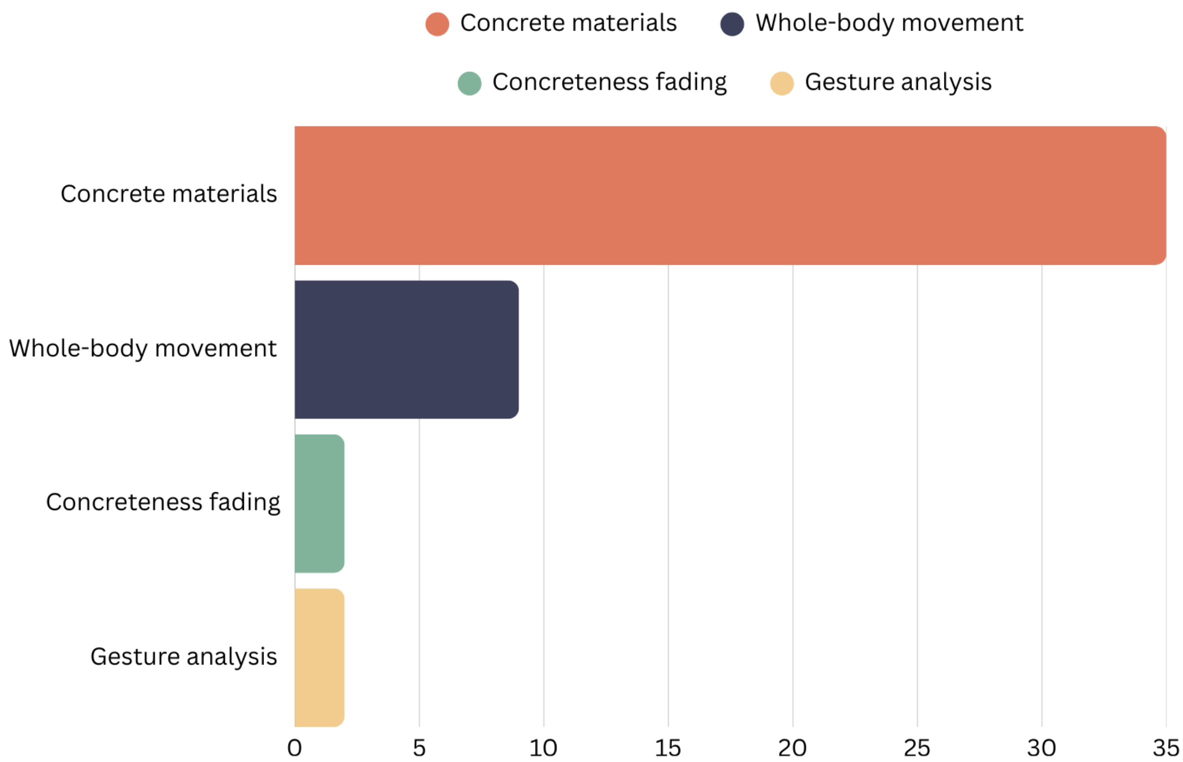


Figure 4.5: Number of studies employing different teaching strategies

porated concreteness fading into the instructional sequences (5%, n=2), these include Hermans and Aivaloglou (2017) who tested the outcomes of teaching programming under two conditions: beginning with unplugged methods and then following with plugged-in (thus moving from concrete materials to more abstract ones) and vice versa. Their results indicated that starting with unplugged activities had a positive effect on students' self-efficacy in understanding the concepts.

Similarly, del Olmo-Muñoz et al. (2020) used a design with two conditions, one in which students started with unplugged and followed with plugged-in activities and one in which students performed plugged-in activities throughout all sessions. Their results also support the use of unplugged activities before plugged-in activities as advantageous to students in both performance and motivation. Lastly, a few studies analysed gesturing in relation to learning (5%, n=2), such as Francis et al. (2016), who analysed children's gestures while programming a LEGO robot from an enactivist perspective and Almjally et al. (2020) who analysed children's spontaneous gestures while learning computing with a tangible interface and with a graphical interface. Their results showed that children who gestured more often showed significantly higher learning gains regardless of condition. Figure 4.5 presents a detailed description of these results.

In addition, I was also interested in which computer science concepts and processes these empirical studies were targeting in their interventions in order to understand their learning objectives. Figure 4.6 graphically represents the frequency of the most utilised computing science concepts and process elements by authors.

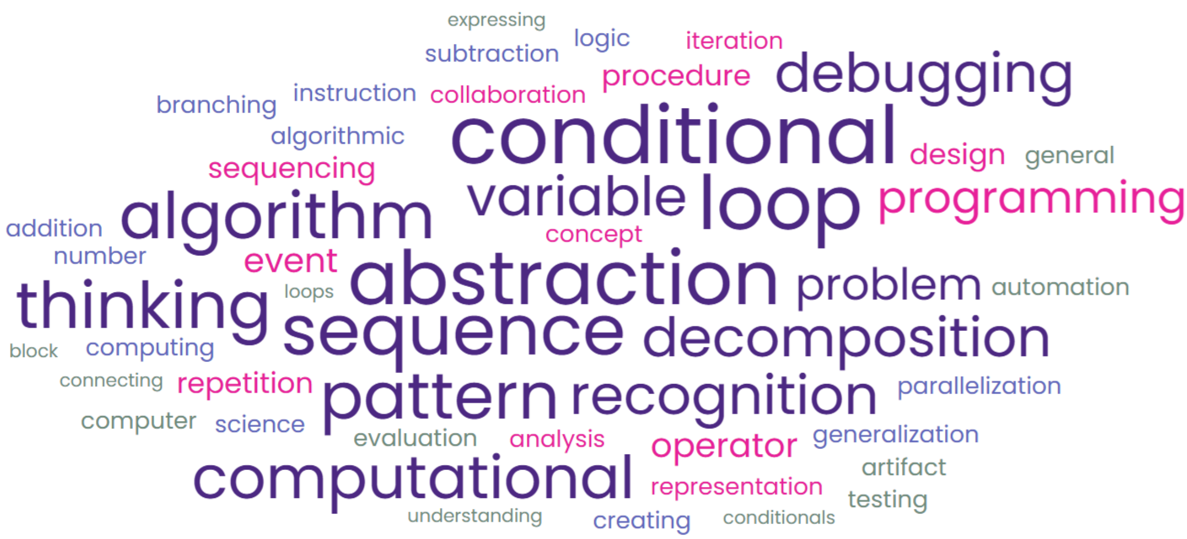


Figure 4.6: Word-cloud representing the concepts targeted in the studies

As shown in Figure 4.6, studies target a wide variety of computing concepts but also some computing practices, such as abstraction or debugging. It can be observed that most of the studies took a holistic approach to CS and CT and decided to design their activities in order to target several concepts rather than focus on one specifically and customise their design accordingly. This is a limitation as it did not allow us to identify activities better suited to teach specific concepts. Out of the 45 selected studies, 38 of them reported the concepts they targeted (the remaining studies claimed to focus on computational thinking as a general skill).

On average, the studies focused on 5 concepts (min=1; max=13; standard deviation=2.9). However, I was unable to find a clear link between the type of activity implemented and the number of targeted concepts, nor between the age of the participants and the number of targeted concepts. In addition, it was not possible to find an association between the type of activity and its duration.

In general, there was a striking lack of accurate reporting in the area, with only 24 out of the 45 studies examined reporting the duration and frequency of their activities and 37 out of the total reporting the number of sessions but not the duration per session. The mean duration for the reported interventions was 8.13 hours (standard deviation 6.78).

The next step in the analysis was categorising the type of outcomes of the studies (learning, cognitive or motivational) and describing the concepts selected as learning objectives in these activities.

Regarding the outcome of the examined studies, I found learning outcomes (those which evaluated conceptual learning) were reported in 58% (n=26) of the studies, cognitive outcomes (those focusing on skills such as reasoning, algorithmic thinking or CT and distinctly do not require conceptual knowledge) in 31% (n=14) and motivational (those which focus on socio-emotional aspects such as self-efficacy or motivation) outcomes in 49% (n=22). These categories were not exclusive, as one study might have focused on assessing several types of outcomes. One study (Cabrera et al., 2019) did not focus on any type of outcome and focused on describing the subject's interaction with the programming tool.

Examples of learning outcomes in the selected studies include Almjally et al. (2020) attainment test, which asks students to create and debug programmes through describing and writing their sequences and assesses their conceptual comprehension through explanation of the solutions implemented, or Wong and Cheung (2020) use of interviews to extract children's learning of programming and how they relate it to other school subjects.

Examples of cognitive assessments include studies which used validated tests, such as Tsarava et al. (2019) use of Román-González et al. (2017)'s Computational Thinking Test (CTt), or studies such as Francis et al. (2016) that used video-recordings of the learning sessions in order to analyse students' cognition based on their actions during a programming task.

Lastly, examples of motivational outcomes include studies which incorporated self-reported assessments of student's perceptions in their own motivation towards computing or their self-efficacy on the tasks, such as Min et al. (2020) use of Likert-scale questions in order to assess students' perceived difficulty and engagement or Minamide et al. (2020)'s survey to assess student's difficulty and enjoyment of the task and materials. A description of these findings and the overlap between types of assessment utilised in the studies is reported in Figure 4.7. Studies focusing on older children (8 years and above) appear to have used motivational outcomes more frequently than those focusing on younger children, while learning and cognitive outcomes were evenly distributed throughout children's development.

For the last question of this literature review, I analysed the technological tools used in these empirical studies to promote computer science or computational thinking. To do this, I mapped the reported technological tools to the activity subcategories from the examined approaches. The technologies utilised in the physical computing categories include construction kits with Arduino sensors (Li et al., 2021; Stupurienė et al., 2021), ciberPLAYce, an interactive programming tool composed of large tangible objects with sensors (Soleimani et al., 2016). For programmable toys, examples include a programmable teddy bear (Jormanainen and Tukiainen, 2020) and educational floor robots such as BeeBot (Angeli and Valanides, 2020), Cubetto (Faber et al., 2019), Dash (Luo et al., 2020), KIBO (Bers et al., 2022a; Hassenfeld et al., 2020) and Mbot (Almjally et al., 2020). Finally, for micro-controllers, there was one study using BBC microbit, microblocks and MakeCode (Cabrera et al., 2019).

For the virtual programming category, several studies used block-based programming environments such as ENGAGE (Min et al., 2020), Kodu and Scratch (Wong and Cheung, 2020), Laplaya (Weintrop et al., 2018), LegoWeDo (Pinto-Llorente et al., 2016), Pirate Plunder (Rose

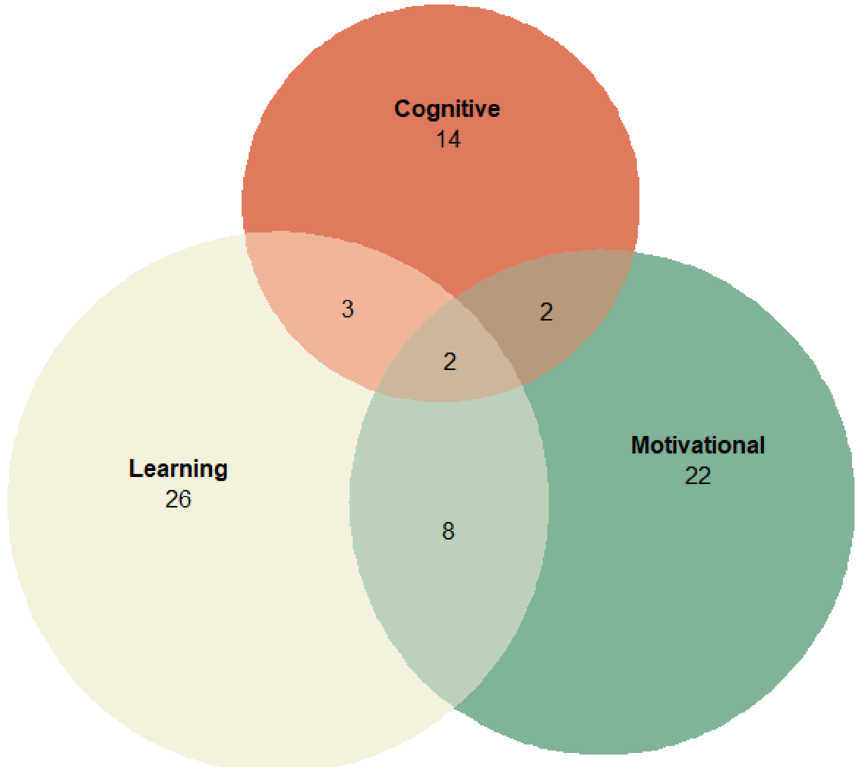


Figure 4.7: Total number of studies assessing each category of outcomes and their overlap.

et al., 2020) and Scratch Jr (Papadakis et al., 2016; Sung et al., 2017). Finally, one study used spreadsheets to support students (Rose et al., 2020). Technologies' distribution is presented in figure 4.8.

Takeaways from study 1:

The aim of this section is to summarise the main points and conclusions from study 1. It is worth pointing I do not aim to conduct a rigorous discussion at this point, as this will be thoroughly discussed in section 5. However, since study 2 will build directly from the results of study 1, I consider it important to summarise at this point the key points extracted for the next phase of research. Firstly, it was clear that the studies observed were heterogeneous in the activities they displayed. Many of the studies used a mixed approach with a combination of unplugged, physical and virtual activities. As such, and taking into account the guidelines established by Kallia and Cutts (2022), I opted to design the activities with the incorporation of unplugged, physical and virtual objects.

Based on the finding that most studies did not include a specific theoretical framework and only a few had mentioned constructivism, constructionism and grounded cognition in their literature backgrounds, it was important to us that the intervention followed closely the conceptual guidelines established by Kallia and Cutts (2022) in the design, as at this point the link between theory and practice in the previous research examined was scarce. Finally, it was important that

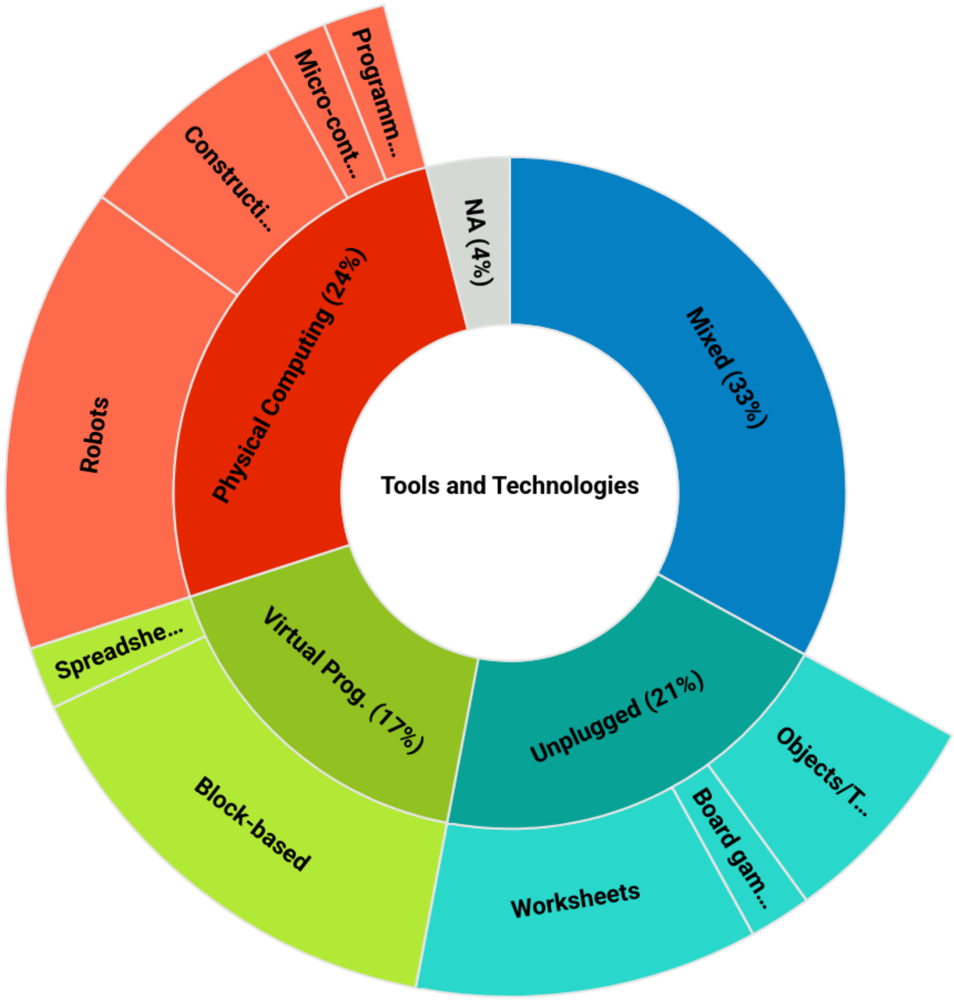


Figure 4.8: Distribution of tools and technologies used in the studies

the intervention capitalised on several of the practices linked to grounded cognition explored by previous research; as such, whole-body movement, concrete materials and concreteness fading were included in the design of the intervention.

4.2 Phase 2: Designing the activity set: listening to participating teachers

As outlined in the methodology section, Phase 2 of this study employed design-based research and participatory design techniques to enhance the feasibility of implementing the model. This study builds on the findings of study 1 as well as the previous conceptual work by Kallia and Cutts (2022), which established several practical guidelines for designing grounded cognition-based computing activities targeted at early childhood. These are thoroughly discussed in section

2.2 but include a high concept-object congruency and the implementation of concreteness fading in both the actions performed by children as well as the objects utilised.

Based on this, an initial set of 10 activities was designed focusing on the concept of sequences. These did not aim to reinvent the wheel; in fact, the main focus of the activities was trying to design them in a way that was familiar to teachers, were inspired by previous research and did not stray much from the habitual practices of an early childhood classroom. I selected for my first set of activities to be designed around the concept of sequencing since it was the most basic of the targeted concepts, as per the literature background in this study, as well as the most explored (along with conditionals) in study 1. This phase included the space for creative exploration, with several activities being considered.

At this stage, my pilot study was conducted, which was useful in assessing the appropriateness and possible logistical threats to the activities, as well as testing the assessment tools to be utilised during the formal study. The main elements introduced to the activity design and intervention plan following the analysis of my pilot study included:

- identifying the need for indicators of understanding in children based on their post-session interviews
- adjusting the length of the activities in order to fit more than one activity per session and maintain children's engagement
- increase the number of activities available within each phase of the EIFFEL model
- incorporating the use of an assessment tool for language skills in the formal evaluation

Figure 4.9 summarises the design process and the information sources used at each stage:

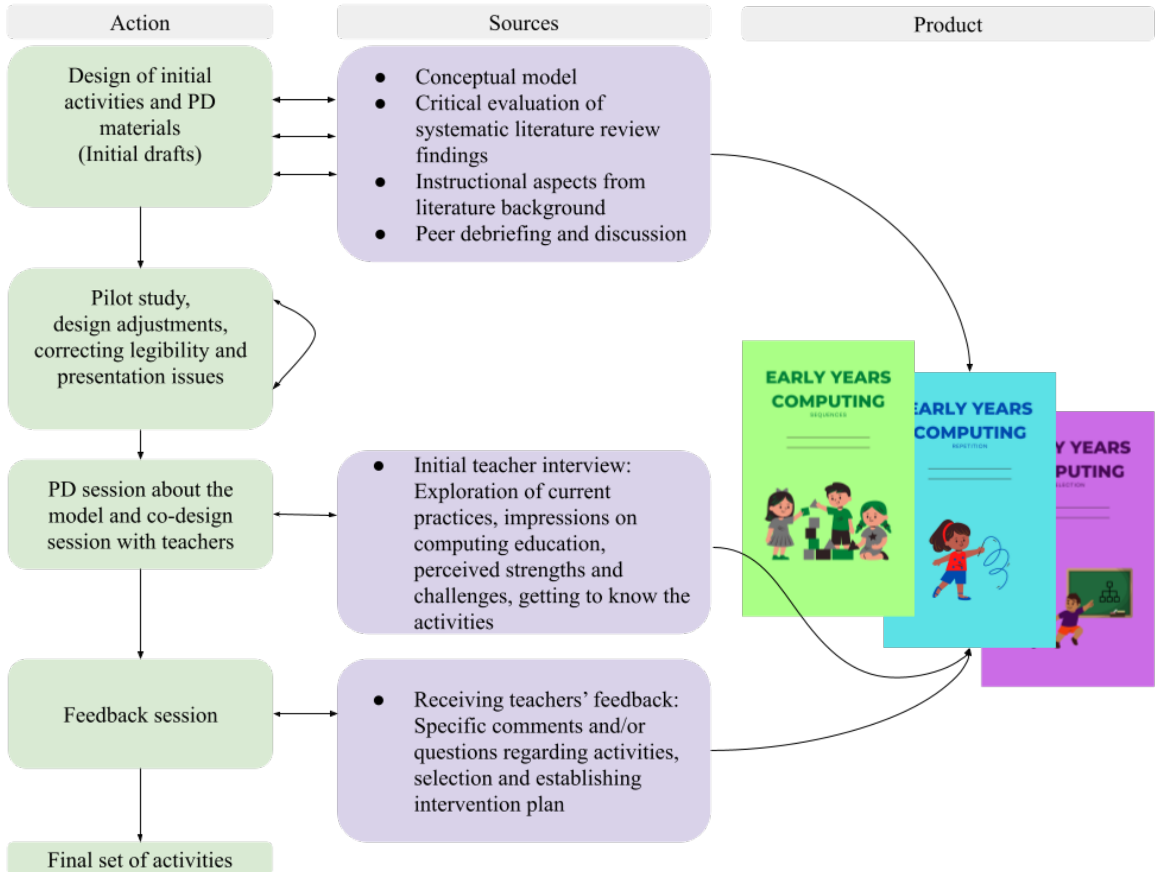


Figure 4.9: Flowchart for co-design process with teachers

Materials for the professional development session are available in appendix A.2.1.

After being explained the objectives of the study and providing informed consent to participate in the activities, the two participating teachers involved in the treatment condition of this study engaged in a two-hour professional development session focused on the model's key characteristics and provided feedback on its applicability. The first hour of the session consisted of a theoretical exploration of the model in which the main ideas behind grounded cognition were conveyed, as well as the model's organisers. This was followed by a one-hour collaborative discussion with the teachers in which they took time to read and discuss amongst themselves the initial drafts of the activities. The aim of this part of the session was address any questions from the theoretical section, build rapport with the participants and establish the general goals of the implementation. Following this session, teachers participated in semi-structured interviews, which explored their background, their motivation towards computing and their impressions of the activities explored.

As for technological materials, the intervention tried to take a minimalistic approach to the use of technological tools in order to try to minimise any anxieties teachers might have in learning to use a new interface. Thus, the initial draft of the intervention comprised mostly enacted physical activities being unplugged, some enacted physical activities using the robot BeeBot and instrumented virtual activities using ScratchJr. The full set of activities is presented in Appendix A.2.2 and the final structure of the implementation in Figure 4.11.

While the full interview script is presented in appendix A.3.1, here I will present their answers using direct quotes, as well as the main themes extracted from the analysis of these interviews. These are organised around teacher A and teacher B: Teacher A is 39 years old and has 11 years of experience as a teacher; she currently teaches one first-grade (6-7 years of age) classroom at the institution. Teacher B is 47 years of age, currently teaches preschool (children aged 5-6) and has 6 years of overall experience.

Teacher's background, previous experiences and motivation towards computing:

Both participating teachers have graduated from tertiary education as regular school teachers. To become a teacher in Uruguay, teachers must complete formal training at a recognised teacher education institution, such as the normal institution (IINN) this is the case for both participating teachers. In order to attend the IINN, it is required to graduate from secondary education, and the programme takes a generalist perspective to education, involving four years of pedagogical and subject-specific study, with its last year being heavily practice-focused. Both public and private school teaching positions are assigned through competitive processes based on seniority and academic performance. The educational track to become a regular school teacher does include classes on technology, but these are heavily focused on ICT and using technology at the user-level. While computing education and computational thinking have been included as elective subjects in the later years, most of the teachers do not have previous experience in the topic. However, as computing and computational thinking are part of the main curriculum, some teachers face the challenge of having to teach something they have received no previous training on themselves. The teachers participating in this study manifested having little previous experience both in bringing computing to their classroom and in their previous education on the topic. For example, teacher A (1st year teacher) manifested having worked with notions of order and having introduced programmable floor robots before in her class, while teacher B (preschool) had only worked with notions of order through picture sequences. When I asked about how they felt their formal education years had prepared them for this scenario, they mentioned:

> *"Very little. I consider there was almost no training at all on this, at least at the time I was studying (to become a teacher), which was a while ago (laughs). During the pandemic there was this "boom" of online courses and I took a few of these, but I do think we have a long way to go in learning these things "*
> — Teacher A.

In this quote, I aim to exemplify how teacher A discussed the feeling of knowing little about the topic of computing. In addition, she points to the pandemic as a pivotal time in which online training opportunities linked to computing and computational thinking started to emerge. Teacher B agreed on the lack of training opportunities for teachers, but provided a different perspective on this, mentioning the high demands for teachers and the short time available to get training:

> *"I do not think there are a ton of training opportunities. You know, sometimes things change in (didactic) approaches and we need to adapt quite fast to a ton of new elements, and that requires time for training which we do not have. I personally have not had experience with computing or computational thinking before, I did start a course but had to drop it because I didn't have time to continue. "*
> — Teacher B.

Despite admitting to having little training on the topic, teacher A displayed a high level of interest in the topic (selecting 5-Very interested in the 5-point likert scale provided). Meanwhile, teacher B showed more hesitation by selecting 3-Neither interested nor disinterested. When being asked about their self-confidence in teaching several subjects, teacher A indicated high levels of confidence in teaching math and language skills, low levels in teaching history topics and being neutral to arts and computing. Meanwhile, teacher B explicitly ranked computing as the lowest confident topic, with maths and language skills again as high confidence topics and art and history as neutral.

Changes and adaptations to the CS curriculum, impressions on the model and perceived challenges:

When inquiring about what changes and adaptions teachers considered the most important when introducing computing science to young children, teacher A emphasises the importance of playful learning and being keen to implement unplugged activities:

> *"I think (play) is really important and sometimes miss that now that i'm teaching first grade, there should be more opportunities for play. I am drawn to unplugged activities because they are fun and simple to implement. But that's it I think, they should have fun. I like the playful approach and the activities seem simple enough".*
> — Teacher A.

Meanwhile, teacher B gave a more succinct answer and circled back to her perceived lack of preparation:

> *"Probably first... becoming more acquainted with the activities. I don't have much experience (with this)"*
> — Teacher B.

When asked about their first impressions of the model and the activities, teachers focused on the practical aspects of the implementation. In addition, their answer tended to focus on the possible challenges as well as their need for pedagogical support:

> *"I'm excited because I feel this is accessible. Sometimes we lack the devices or if they (the children) have to take tablets or robots home they do not take care of them and they often come back broken. I feel like I could implement this with my training (...) There should be more support for teachers, maybe extra time to take courses and training opportunities and support from the institution. But specifically, didactic and pedagogical training... I thought the theory was interesting and it's something we should pay more attention to...*
> — Teacher A.

The need for devices in computing education and how these presented an operational and practical challenge for teachers was also a worry shared by teacher B:

> *"They don't have the proper care (the devices), most are broken, or missing a charger... having to teach using devices means I have to test things first and sometimes I don't even have the right materials. We have many things to do and it requires a lot of time in preparation, I think unplugged activities would work better because of that "*
> — Teacher B.

Awareness of concreteness fading and model's principles and needs:

I specifically asked teachers about their familiarity with grounded cognition principles and one of the central aspects of the model: concreteness fading. While teacher A was able to relate the concept with practices in other topics of study, teacher B manifested she was not aware of this idea:

> *"I do tend to focus on going from something more concrete before going for something more abstract, I think students find this helpful, we do it a ton in math for example where they need the support from (concrete) materials first"*
> — Teacher A.

> *"I hadn't heard of concreteness fading before... I think what is needed to plan this sort of activities is time. As for the meta-cognitive section, I think that is more of a standard practice."*
> — Teacher B.

Finally, the last theme of the interview regards their needs as teachers and what actions can be taken to support them. Teacher A specifically mentioned she was worried about the multiplicity in learning theories and confused as to which direction to take:

> *"I do think we would be better if we had the correct tools. The training is very uneven as well, you have teachers that learnt with more behavioural methods and direct instruction, teachers who learnt under constructivism and now there's a more competencies based approach and these new fields. I worry sometimes there are fads in education and we (teachers) don't quite know how to navigate that. You always need to improve your practice yet sometimes you feel... alone. In my opinion it (training in computing) should be part of mandatory training, not just optional like it is right now"*
> — Teacher A.

Meanwhile, teacher B mentioned she struggles with the current curriculum as well and some excitement about having a set of practical activities:

> *"The curriculum should be clearer, what is the relation between the actual content and students' performance. It's hard to imagine a trajectory. Also, as I said, we need proper devices and time to actually plan the activities. I think this (the activities) at least gives you a starting point, but I need to read them more carefully".*
> — Teacher B.

Based on teachers' responses and their explicit worries about not having enough time to prepare, I decided to modify the set of activities to make them less narrative and highlight the key aspects of the model.

Changes during this stage included introducing a brief and simple definition of each of the targeted concepts, clearly stating which type of activity each was (i.e highlighting using colour whether the activity was enacted or instrumented and whether it used physical, virtual or mental objects) and what was student's role (actor, issuer or author) in order for them to have a clear connection between the theory and their practice.

In addition, I improved the description of each activity and added examples of specific metacognitive and reflective prompts that teachers could use at the end of each lesson. Once these changes were addressed, teachers received a new copy of the activities and were encouraged to ask questions and provide feedback regarding the structure.

Below, I present an example of the first activity and the design features incorporated as the final version, incorporating teachers' feedback.

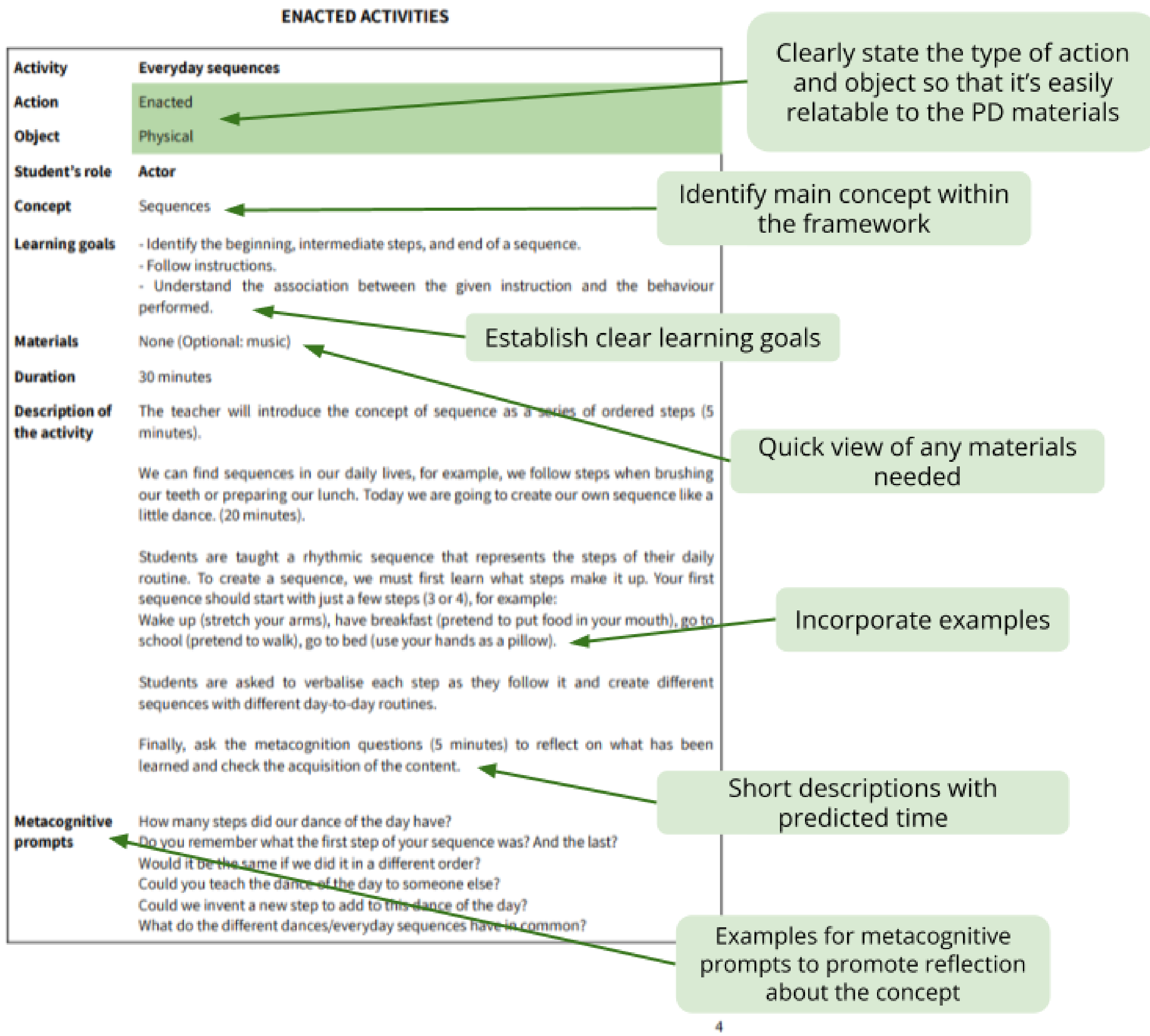


Figure 4.10: Activity design

Both teachers manifested they were worried about the time for preparing each of the activities. Given that the average allotted time they would have on their schedule would be approximately 1.30 hours per week, it was agreed that shorter (30 minutes or less) activities could be implemented at a rate of 2 per week, while longer (45 minutes or more) activities could be implemented weekly. Thus, it was necessary to select a set of activities that was sufficiently representative of the stages of the model and encompassed all three concepts while providing opportunities for connection and practice. At this stage of the process, teachers manifested a good understanding of the activities and did not provide any significant changes or concerns regarding their structure or content, and thus a final version was created. The set of activities to implement was selected in agreement with the participating teachers in order to fulfil the requirements of the model's conceptual trajectory as well as prioritising their concerns about requiring preparation time or many materials. The final set of activities conducted in each lesson is presented in figure 4.11.

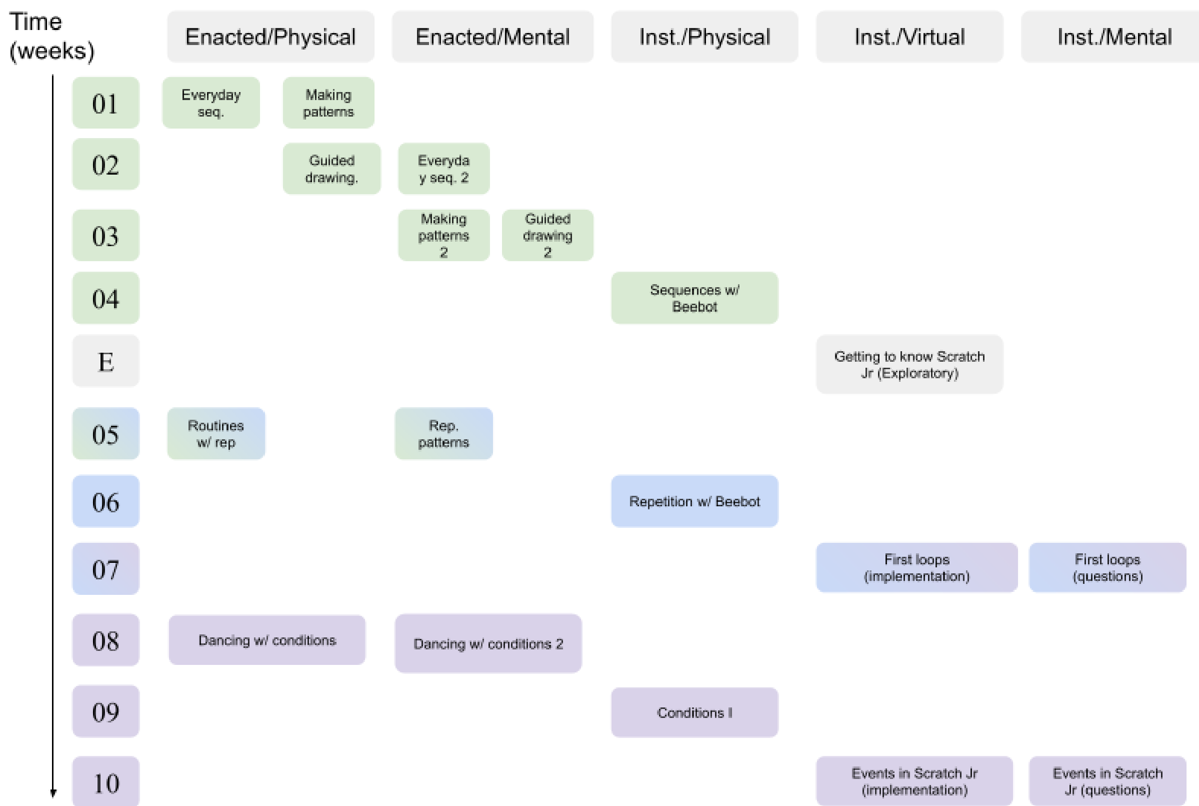


Figure 4.11: Activities implemented per lesson.

4.3 Phase 3: Applying the model in real-world classrooms

In the following section I will present the results from phase 3, which encompasses the empirical application of the intervention co-designed in phase 2 of research. As stated in the methodology section, the first research question consisted of conducting classroom based ethnographic research in order to identify indicators of understanding based on the implementation of the activities. This is described in subsection 4.3.1. The research questions in phase 3-B are twofold; firstly, I aimed to examine whether the intervention was successful in improving children's computational thinking assessed through an independent questionnaire (Zapata-Cáceres et al., 2020). In addition, I wanted to understand whether developmental variables such as language skills and executive functions played a role in predicting student's performance. Secondly, I wanted to describe students' learning trajectories in conceptual understanding through a microgenetic approach, as well as identifying learner profiles. I describe these results in section 4.3.4.

4.3.1 Phase 3-A: identifying indicators of conceptual understanding through the lens of ethnographic observation

In this section, I present the findings stemming from the 10-week ethnographic observation of classroom activities.

Firstly, I must provide sufficient contextualisation to ensure the ethnography is analytically sound and meaningful (Pole and Morrison, 2003). Providing ample context is essential for situating the scene within its cultural, social and spatial characteristics, as well as analysing each classroom's organisation, micro-cultural practices and social interactions. This phase of the study presents an integrated approach to data analysis that is consistent with ethnographic research, in which both interviews and observational data are used as sources in identifying key themes that emerge from the empirical data. In ethnography, these are not used as discrete sources of evidence but as complementary means of approaching the multiple characteristics that comprise the classroom setting (Hammersley and Atkinson, 2019; Pole and Morrison, 2003).

Next, I present my findings organised around key themes that integrate these elements. I will discuss each theme in detail in order to provide a comprehensive understanding of the patterns and behaviours observed within the classroom, as well as introduce direct extracts from the activities to evidence the abstracted themes.

Characterising the classrooms: defining my empirical setting for ethnographic research

In this section, I aim to set the scene for the analytical process by providing snapshots of the classrooms that formed the basis of the reflexivity required for ethnographic research. The descriptions are condensed descriptions of a regular day in the classrooms. The environmental descriptions must be the starting point for every ethnographic account, as they will aid readers in characterising and contextualising the observations presented below.

The studied groups consisted of two classrooms and their respective teachers. All participants are from a mid-sized private institution located in Montevideo, Uruguay. Classroom A is a first-grade class comprising 16 children aged 6 to 7 with a teacher who is 39 years old and has 11 years of teaching experience. This class comprises 12 boys and 4 girls, and one is suspected to have a neurodevelopmental disorder, but nonetheless has not yet received a proper diagnosis. The classroom is organised traditionally, with individual benches facing a single whiteboard. The space is decorated with children's art as well as visual aids for learning the alphabet and seasons. There is a desk at the front corner of the classroom designated for the teacher, but she prefers to stand and move around the classroom to help students.

Overall, the organisation of the class regarding the placement of furniture and equipment is highly traditional, placing the teacher at the front of the class and students in a secondary position, which, while it facilitates their attention to her, sometimes seems to work as an element of authority. The class is located near the corner of the building, which means it can be quite noisy from outside traffic. For computing activities, the teacher asks children to come to the front of the class and sit around a circle on the floor, breaking with their usual organisation in desks. This seems to excite children most times, on some occasions causing them to run or skip around the classroom before arriving at the new proposed configuration of sitting in a circle.

Teacher A is soft-spoken most of the time, but sometimes struggles to manage children's behaviour and can have instances of behaving in a way that reflects worry or anger. Throughout my observation, I was able to notice brief moments in which clear expressions of tiredness were had, such as long sighs before acting or pauses for observation, as if she was trying to regulate her own behaviour before interacting with the children. Sometimes this is reflected in verbalisations that mix a tone of affection with worry, such as *"What am I going to do with you?"*.

Some elements of the classroom reflect efforts in creating pedagogical agreements and timetables that structure their daily activities and signal transitions for children. On the board, there is a schedule for the day written on most days and a monthly schedule printed using the computer. In addition, pedagogical agreements such as behavioural rules are often referred to throughout the time of my observations. While the organisation of the classroom in terms of the placement of furniture and materials reflects the asymmetry of the teacher and pupil's roles, I observe instances in which the teacher tries to assert authority but is unsuccessful. For example, before transitioning between different activities into the computing activities planned for the day, she asks children several times to put previous materials away and gather for the next activity. The ways in which she signals discomfort with a child's current behaviour are multiple, such as changing the inflexion in her voice to a more stern or serious tone, increasing her proximity to a specific child or using their name to get their attention. While directions do happen in the classroom, these are not expressed in an authoritarian tone but through efforts of trying to create consensus by providing children with explanations as to why they are doing what they are doing. For example, she often uses expressions that create reasons for a specific behaviour, such as *"We are going to gather in a circle so that we can all share the materials"* or *"This part requires us to be very focused so that we can learn it together"*. Her use of "we" instead of "you" creates a collective culture of the group: in fact, the moments in which she refers to individual children instead of the group as a whole are scarce throughout the activities and often reflect a more intense effort on the part of the children to regulate behaviour. Calling someone by their name is used as an explicit signal of behavioural disregulation, and children are aware of this, often resorting to this themselves in order to express discomfort with another student's behaviour.

This is especially seen in moments where a particular student (pseudonym: Gaby), who is suspected to have a neurodevelopmental disorder but has not yet received an evaluation and differential diagnosis, struggles with regulating her behaviour in the class. Throughout the computing activities, she is often distracted and tends to move around the classroom exploring various objects, and her name is called several times throughout the activities by both the teacher and her classmates. In at least one activity, extra help was required from an auxiliary teacher who spent one-on-one time with her in order improve the class's climate. On one occasion, as I am doing my observation, this teacher expresses to me some feelings of helplessness in sorting some of these challenges alone: *"See, this is impossible without help"*. Among the children, social roles seem to be stable. Throughout the activities, I observe that groups of children who prefer to work with one another are consistent, reflecting that the classroom is fragmented into different "friend groups" that seem to be based on affinity, proximity and gender. The last point is particularly relevant, as I do observe somewhat of a gender divide socially among the children when asked to form pairs or small groups, with girls making their preference to work with other girls more explicit to the teacher. Despite this, I also observed active efforts on the part of the teacher to create unity within the classroom, often pairing or grouping children herself for different activities so that children have opportunities to interact with a variety of students.

Despite brief moments of tension, the relationship between children and their teacher seems to be deeply affectionate, they call her by a nickname rather than her full name and in several instances I observed children express interest in her daily life. One boy in particular (A, boy, 6) who throughout the activities enjoyed sharing examples of his activities at home in relation to computing and focused on sharing his experience, also tended to ask his teacher about her day outside of school.

Classroom B, on the other hand, is a preschool classroom comprising 7 children aged 5 to 6 with a teacher who is 47 years old and has 4 years of teaching experience. It has 3 girls and 4 boys. The teacher is very soft-spoken and the class organisation is strikingly different from that of classroom A, as it presents the organisation of an early childhood classroom: there are several play/learning stations with space for symbolic play, equipped with dolls, boxes and fabrics for children to play with, a station for construction play equipped with plastic blocks and beads, a station for book reading and a space for puppetry. This marks a stark difference regarding classroom organisation, as children seem to transition between activities more organically. For example, as I enter the classroom to begin my observations, I often notice children are using their different play stations in an organised manner, conversing with each other.

There is a whiteboard at the front, and the class is also decorated with children's work from previous lessons. In addition, it usually displays' children's packed schedule of activities which include not just computing time but also gym, motor skills, English and theatre. I notice more activities are implemented in the school for preschool-aged students than for primary-aged students, despite only having a 1 year difference between them. This seems to suggest a symbolic change of culture between preschool and primary, in which primary children are viewed as more academically minded, while preschool children are given more opportunities for playful learning and learning through extra-curricular activities. This is also reflected in the amount of materials available to students freely in preschool vs in the first year of primary: while primary students in classroom A often focus on their notebooks and perform pen and paper-based activities, children from classroom B have more sensory materials available, free and symbolic play stations, and concrete materials such as beads and building blocks.

When computing time arrives, however, the children in classroom B also gather in a circle on the floor surrounding the teacher, just like in classroom A. This also creates an explicit signal of novelty; moving together to the floor seems to express that there is something new and important about to be presented to them.

Pedagogical agreements, behavioural rules and regulating behaviour are more relaxed in this classroom; throughout my observations, I recorded very few instances in which teacher B had to call for a child's attention or try to manage their behaviour. In the instances in which it happened, similar strategies to those of teacher A were used, using tone inflexions and calling a student by their name to get their attention.

In contrast with classroom A, the micro-culture surrounding learning is less focused on providing ample explanations and reasoning behind every action, but in creating routines and rituals that facilitate the transition between activities and capture children's attention. For example, before beginning a new activity, teacher B sings a small song that requires children to join her and sing along with her and immediately signals them that a change of activity is about to happen. In addition, I observed children has a very clear routine that was evident both by their schedule visualised in the classroom and children's manifestations of their expectations surrounding the activities. In several instances, I was able to observe children asking their teacher about what was coming, such as: *"Teacher, after we finish this we are going to gym, right?"* which shows that the class routine seems to be stable enough that children know what to expect.

The relationship between children and their teacher was respectful and democratic, with the teacher consulting children and allowing for moments of participation throughout the activities. Overall, while less overt displays of affection were observed in this class between the teacher and the students, there was also less conflict present within the classroom regarding behavioural control. In fact, children had very few issues with following the activities and participating in each proposal made.

Lastly, the social relations between the students were equally distributed. In this classroom, I was not able to observe evident groups of friends at first, although these were more consistent towards the end of the sessions. Similarly to classroom A, the teacher also used pairing and group strategies in order to promote socialisation between all children in the classroom.

In the next sections, I will present the findings from my ethnographic observation organised into themes focused around a central question: what indicators can be identified in the classroom that signal children's understanding?

Theme 1: Enactment in the classroom

As presented in the literature background, enactment was defined as any use of physical actions to represent an idea or a previously conducted activity. This includes gesturing, the use of the body and other objects to mimic the activities.

Throughout the activities, I observed children frequently utilising enactment as a tool for both understanding and reinforcing their conceptual knowledge. However, an important distinction one ought to make when interpreting children's use of enactment in this particular learning environment is that, while as humans we often use gesturing to highlight communication, I am specifically referring and will focus on enacted explanations, as the actions being performed and the concept being conveyed are intimately linked. In their enacted explanations, concept-action congruency is especially relevant, meaning that the movements being performed are semantically related to the concepts. These are thus more focused on conceptual understanding than other activities which include movement or are more linked to behavioural control.

Throughout the observation, there were several examples of how movement within the classroom is often used to cultivate self-control and signal important activities. For example, teacher A sometimes struggled to get children's attention and she raised her hand in order to signal to them that they should be focusing on her or had something important to say. Examples such as this abound in education, as the embodied nature of learning is present at every minute in the classroom, especially in early childhood and first year settings where movement is typically less restricted than at later stages in compulsory education.

It is important to highlight that enactment was a theme in the design of the activities, and thus as one of the stages described in the conceptual model defined by Kallia and Cutts (2022), it was expected to appear throughout the implementation as what I will refer to as teacher-supported enactment: meaning instances where enactment happens because teachers overtly ask children to use their body for an activity or model enactment for them using their own body.

As stated, teacher-supported enactment was an integral part of the implementation of the model. The importance of conceptual and action congruence was highlighted during the professional development sessions and teachers showed special interest in this aspect, even before the implementation started, as presented in study 2. Teachers displayed openness in engaging with unplugged activities and guiding children through a more structured path towards increasingly abstract actions and objects.

For example, during an activity in lesson 1, teacher A proposed students to think about a task they do often such as eating their lunch. Here I present an extract as an example of an enacted activity that requires teacher-supported enactment.

> As usual, she asks children to get away from their desks and come form a circle on the floor at the entrance of the class. A few children do so right away and wait, while others remain at their desks and take a while longer. Once everyone is seated,

> the teacher explains that they are going to work on a sequence of steps to do this daily activity.
>
> The sequence is constructed with the students and is agreed upon as follows: first, wash your hands; next, get lunch out of the container; then, eat your lunch; next, close the container; and finally, save it in your backpack.
>
> The teacher accompanies each step of the sequence with a movement representing the step. For "washing your hands" she puts her hands together and pretends to lather; for "get lunch out of the container" she uses both hands and separates them, mimicking the opening of a lid; for "eat your lunch" she uses her right hand with her fingers positioned as if she were holding a spoon or fork, and slowly moves her hand towards her mouth to mimic eating; for "close the container" she extends her hand in front of her and moves it downwards, as if closing a lid; finally for "save it in your backpack" she uses both hands to pretend she's holding a container and slowly turns around, as if her backpack was behind her.
>
> The teacher writes the sequence on the whiteboard in simple words and goes over it with the students. She explicitly defines sequence as "a series of steps" and asks children to think about other sequences in their lives. Some children come up with similar sequential processes: *"washing your teeth"*, *"going to bed"*, some shout.

The activity showcases a typical example of teacher-supported enactment, in which the very act of using enactment to consolidate the concept is embedded into the activity itself. In this particular case, it was observed that the teacher created clear movements for each of the steps in the sequence. Most importantly, it was a sequence that children were highly familiar with as it was part of their daily school routine. When it comes to defining the concept and providing students with opportunities for lexicalisation in this context, it was observed that she used an embodied metaphor for the concept.

Most concepts in computing constitute abstract notions. These are often simplified for educational purposes as embodied metaphors, or expressions that arise from our physical experiences and interactions with the world and use movement or physical description to convey to children abstract notions such as the ones presented in this study. This embodied metaphor in particular, *"A series of steps"*, which compares sequences with movement, was spontaneous on the part of the teacher, as we did not highlight the role of embodied metaphors in the presented activities. We observed that this particular metaphor proved educationally relevant and intuitive for students, as in later sessions, children began using this phrase spontaneously as well in order to describe sequences. This was also often accompanied by gestures and movements that conveyed the idea of events through time.

It is worth noting that Teacher A chooses to present a more extended sequence to her students (materials suggested up to 4 steps to be included for this age bracket). The chosen sequence included five actions and the selected movements to accompany them. I observed that the length of the selected sequence might have had an impact on children's understanding and ability to create their own examples. When asked about this after the activity, teacher A mentioned she felt confident her students were familiar enough with the activity and would not have a problem with understanding. Moreover, she finishes her explanation with a request for transfer: she asks students to think about other sequences in their lives that are similar to the one they had just worked on during the activity.

Here, however, I want to focus on the process of spontaneous enactment, meaning when children use their body, movement or gestures to convey an idea or support themselves while trying to solve a problem. I will use an extract from an activity from session 4, in which these same children from teacher A's class independently implement enactment as a problem-solving strategy. Moreover, I care to highlight the collaborative nature of this process, as one child first spontaneously uses it and then others start to pick up on the strategy and implement it as well:

This activity involved creating a sequence using Beebot in order to reach a fixed objective (a honeycomb). The problem at hand was presented for children to solve as a group and is depicted in Figure 4.12

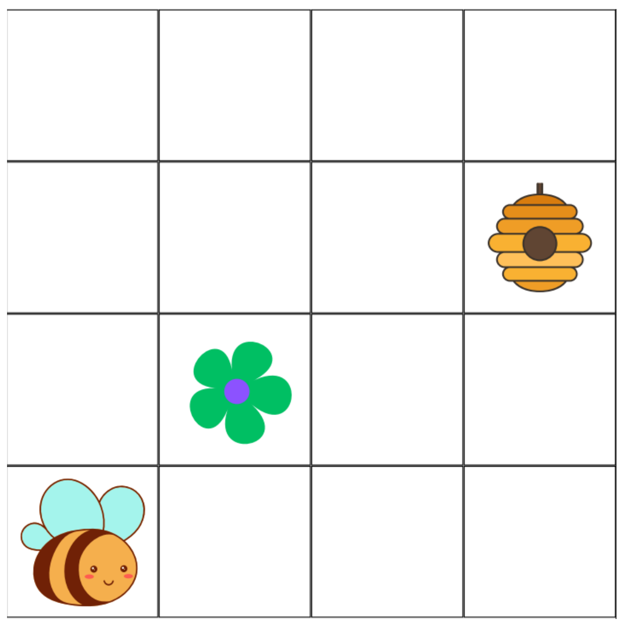


Figure 4.12: Example of one the tasks with BeeBot, children would need to start at the Bee and programme the robot to reach the honeycomb.

Before beginning, just by looking at the BeeBot, some children start to speculate on the nature of the robot.

F, boy 6: "Does it have hands?"
Ag, boy, 6: "I think it has motors"
Teacher B: Who remembers what we discussed last time about sequences?

Two children raise their hands. **Teacher A**: “I want to listen to new voices, not the ones that always participate, let’s see”.
F, boy, 6: “A sequence is something that repeats”
V, girl, 6:“A sequence has a couple of steps”
R, boy, 6: “A sequence has steps that repeat, it could be colours like red, yellow, green, red, yellow, green”
Teacher A: Do they always have to repeat?
Ag, boy, 6: “I don’t think so, they need to be ordered”
Teacher A: “Well done!”
Teacher A then introduces they are going to use the robot to create a sequence: she presents the buttons on the robot and tries to establish its way of usage. She has children explore the buttons and come up with hypothesis as to the functionalities of each. The children work on their understanding of directions. She explained that since they are sitting opposite, their right/left might be backwards from hers. Most children are able to identify left and right with help. One child relates the directions with the “train of colours” they created before (R, boy, 6). Then, she introduces the idea that the X button erases the program they have created so far. Afterwards, she explains the overall task: children need to create a sequence for the robot in a pirates-themed mat so that it goes from the start, passes through a map and a telescope and reaches a treasure. Teacher B then proceeds to model the activity for the children and asks them to think of the trajectory as a group. She puts the question into words and uses decomposition to divide the task into smaller steps for them. She introduces they are going to use the robot to create a sequence: she presents the buttons on the robot and tries to establish its way of usage. She has children explore the buttons and come up with hypothesis as to the functionalities of each. The children work on their understanding of directions. She explained that since they are sitting opposite, their right/left might be backwards from hers. Most children are able to identify left and right with help. Children then take turns trying to move the robot. Most however are not able to move it past 2 steps at this time. While the children are sitting in a circle, one of them (F, boy, 6) stands up when he gets his turn. He pretends to be the robot to count the number of steps as he looks at the mat his first try is unsuccessful but he manages to reach the goal at his second try. As other children observe his strategy, they begin to copy his actions in subsequent turns.

The extract described above is from an instrumented activity with a physical object session using a floor robot programmable through the use of buttons depicting directional arrows. It can be observed that decomposition is needed to complete this task, as although the mat is relatively small (4x5, composed of 15 cm tiles) the shortest trajectory towards the objective still had 5 steps, which proved hard for children to retain, especially as they did not have any supplementary materials to "save" the programmes they created and had to rely on memory.

Before even starting the activity, children displayed an increased excitement based on the fact that they were going to include new materials, particularly a floor robot, into the activities. Moreover, children begin to speculate as to the functions of the programmable robot and how it might be operated.

In the present activity, children are instrumenting their programs by issuing commands into a programmable object, albeit in a 3D space. Despite it theoretically having a lower level of embodiment, thinking tools learnt during the first phase persist while using the robot: after several attempts, one of the children pretends to be the robot to facilitate the path-planning solution. It is noteworthy that the strategy started to appear after several attempts and a brief period of familiarisation with the tool itself, primarily as a way to prevent perspective-taking errors.

I observed that children faced difficulties in navigating the space of the mat particularly during turns, and thus in this case enactment was used as a way of creating a first-person experience.

It is important to point out that task difficulty seemed to be an important factor while observing children's spontaneous use of enactment. Particularly, when tasks seem easier for children they seemed to require less use of enactment. Consequently, I observed more frequent enactment during more advanced lessons, especially when it came to representing the notion of repetition. However, it is worth pointing out that while enactment was often a good strategy for modelling an expecting result before executing their programme, it was not without its faults. For example, if children's theoretical enacted model did not align with the movements of the robot due to noise in the planned trajectory such as low battery or irregularities in the floor. This required work on part of the teacher to scaffold and encourage using enactment as a model and using the meta-cognitive prompts later on in order to consider why their trajectory might not have gone as planned. This idea that the robot's situated movement might not necessarily coincide with children's theoretical model of what is going to happen has been previously referred to in computing education as the "notional machine" (du Boulay, 1986) meaning the simplified model of how a computer or device executes its programs (Fincher et al., 2020a,b). This connection is further discussed in section 5.4.

Theme 2: Displays of causal reasoning

A second theme I identified throughout the fieldwork was the way children began to understand and reason about the cause-and-effect relationships in the activities they conducted. In the previous section, I showcased how some children used enactment to support their reasoning while constructing a spatial sequence using a floor robot. However, I primarily recorded the use of causal reasoning through verbal cues, meaning children outwardly discussed their strategies with the teacher or their peers, explaining their behaviour.

Here I present an observation fragment from an activity in which children were tasked with creating a sequence that contains a pattern as an introduction to the notion of repetition within a sequence. They were able to choose their own pattern, as long as the sequence contained repetition within. According to the literature, inferential reasoning is linked to concept formation through the process of abstraction; for example, through inductive reasoning, a child might observe several types of toys and infer the characteristics that define the concept of "toy." This is the first aspect of concept formation as defined by Sloutky's model (Sloutsky, 2015) in my literature background. Once formed, concepts are applied in new situations using inferential reasoning, allowing individuals to predict or understand new instances by comparing them to previous categories. Thus, the presence of causal reasoning as a theme provides us with valuable information regarding their conceptual understanding.

In a recorded exchange between two children while they were working together on creating their sequence:

> In classroom A, one of the groups used only 2 colours, but most teams used 3 or 4. One group in particular (F and E) have a very specific and clear idea of what they want. They start by organising the beads grouping them by colour before creating their sequence. Then, they check each colour one by one following the correct order.
> At one point, E picked up the wrong colour bead according to the pattern:
> **F, boy, 6:** "no, not that one, you need to put a red one next, If you put that one you will break the pattern".
> E corrects according to his classmate's instructions.
> **E, boy, 6:** "I don't think we have enough beads".
> **E, boy, 6:** "We are going to need more blue ones if we want to continue".

In the brief fragment presented above, it can be observed that participants F and E display planning abilities, an integral part of reasoning. They start their approach to the activity by organising their materials into colour categories. While observed, this strategy was fairly unusual, as most children approached the task by creating an initial pattern and then evaluating which coloured bead they needed and searching for it each time. The strategy presented above is more time-efficient. Moreover, participant F is displaying problem-solving abilities (he is aware of the task's objectives, he is executing the task accordingly and has identified an error in the pattern). Participant E is also participating in solving the activity; he has identified that, based on their current set of materials, they are unlikely to have enough beads to finish their selected patterned sequence. The use of causal structures of the type *"If you put that one, you will break the pattern"* and *"We are going to need more blue ones if we want to continue"* was observed in children that showed the best performance in the activities. Throughout the activities, teachers made an effort to use metacognitive prompts and questions in service of causal reasoning abilities: they asked evaluation questions such as *"What do you think will happen next?* to provide children with an external opportunity to assess their steps and regulate their behaviour. At perhaps a higher level of difficulty, they asked children to come up with alternative solutions.

Theme 3: Use of vocabulary and language

Finally, the last cognitive indicator regarding children's conceptual understanding was their increasing use of specific vocabulary throughout the intervention.

Towards the end of the intervention, children made explicit use of the words "sequence", "condition" and "repetition" in the explanations of the activities. In accordance with Sloutsky's model (Sloutsky, 2015), putting newly learnt words into use is the process of *lexicalizing* or using the correct label to refer to a specific concept.

In the next example it can already be observed that some of the children start to identify and highlight the notion of sequence as a new concept and label to use. Moreover, one girl (participant V) reiterate the same embodied metaphor used by her teacher in session 1: *"A sequence has a couple of steps"*. The example also displays some children use vocabulary somewhat confusingly, such as participant F, who identifies a sequence as *"Something that repeats"* or participant R, who uses the concept in the same way, this time providing an example.

> Children are gathered in a circle with their teacher, they are all sitting on the floor. They have just talked about conditions and the teacher has asked them to think about examples in their daily life where they can find conditional statements.
> **M, girl, 6**: Scratch Jr?
> **Teacher**: We saw a condition in Scratch Jr, but what about other examples?
> **F, boy, 6**: Like if you are playing a game of statues, the condition is that when the music stops, you need to freeze (he demonstrates this with his body).
> **Teacher**: Excellent
> **R, boy, 6**: The thing with the condition is you **need** to do it, it has to be met for something to else to happen
> **Ag, boy, 6**: I have an example of a condition... for example if you are naughty, your parents might say it's ok on the condition that you do not do that again
> **Teacher**: That could be an example...
> **M, girl, 6**: In a sequence the condition is that a certain step needs to come before another one
> **Teacher**: Very good!

Here I presented an example of the use of specific vocabulary in one of the last sessions during lesson 10. This example stems from the moment both the teacher and their children reflect on what they have learnt during the session, and is an opportunity for meta-cognitive scaffolding.

I was able to observe how different children associated the concept to different elements throughout the activities: while participant M uses an example from a phase 2 activity in a virtual environment (their exploration of events triggering based on a condition during a task of programming using ScratchJr), participant F uses an example from an enacted activity and uses his body to explain the condition underlying a simple game of statues. I consider both examples to be correct here as they both highlight an underlying condition within the structures.

Finally, participants R and M summarise the concept highlighting one of its essential elements *"The thing with the condition is you need to do it, it has to be met for something to else to happen"* and *"In a sequence the condition is that a certain step needs to come before another one"* in an expression that uses both concepts accordingly. Meanwhile, participant Ag provides a similar, situated example to that of participant F.

Throughout the activities, I observed an increase in children's use of the specific vocabulary and labels regarding the targeted concepts. Interestingly, I also observed some integration, such as seen in participant's M summary integrating the notion of a condition within a sequence, or participant F and R as shown in the previous example identifying that sequences might have repetition within as well.

The next section highlights the themes identified as supporting students' conceptual understanding throughout the implementation that include affective aspects of learning and their effects on children's understanding.

4.3.2 Affective and social indicators

Children's engagement and affect

Affect is widely recognised as an integral part of learning. As such, it was expected and corroborated through my observations that throughout the entire implementation of the activities, affect and engagement worked as a precursor of task-accomplishment. During most of the activities, the teachers needed to hold a highly active role in promoting behavioural control through affective statements of encouragement such as *"good job!"* or *well done!* while also promoting task engagement by redirecting students' attention. In these examples, verbal encouragement is displayed. Affect was engaged in all participants, with children practising soft-skills such as interpersonal problem-solving and compromising throughout the activities.

Interestingly, I was also able to observe that children engaged affectively not only with each other and their teacher but also with the materials involved, during the introduction of the floor robot.

Specifically, I observed higher engagement and changes in their causal reasoning about their programmes caused by the attribution of intention to this object. As social beings, research has found we attribute more value when we believe there is intentionality behind actions than to the mere physical movement of inanimate objects (Airenti, 2018; Tomasello et al., 2005). As such, we observed for young children the fact that the robot had a face and animal-like characteristics affected the way they thought about and hypothesised about this object that was different from when they worked with other concrete materials. Specifically, younger children (5 year olds) often attributed intentionality to the object.

The importance of this attribution of intention diminished throughout the activities and was more present in children with poorer performance in the resolution of the tasks. Here, I present an example of a conversation between two children and their teacher regarding intentionality in the use of the floor robot towards the end of one of the activities:

> To finish the activity, the teacher decides to model the correct trajectory.
> **Teacher:** Shall we make one altogether?
> Most children are excited about being able to share the task with their teacher. She shows them how she takes some time to think about it, and how she needs to plan ahead the trajectory first. After the modelling on part of the teacher, they go back to sitting in a circle and start discussing the activity:
> **Teacher:** What sort of movements can our robot do?
> **Ag, boy, 6:** Four, right, left, forwards and backwards.
> **Teacher:**: Good! and what happened with the programme we made?
> **G, boy, 6:** Sometimes he got confused!
> **Teacher:** I do not think he got confused…
> **Ag, boy, 6:**: We were not giving the right command!
> **Teacher:** That's right, remember we programme the robot based on how we wanted it to move. Maybe we got confused in the direction sometimes…
> **G, boy, 6:** I think it went mad.

In the discussion above, it can be observed that participant G attributed intentionality to their floor robot by exclaiming the reason for its behaviour was confusion, a human characteristic. As such, this participant is not identifying himself as the author or issuer of the program being created, which impacted on his understanding of the task. Thus, it can be seen how salient attributes of some materials, such as the capacity for attribute intentionality based on human or animal-like characteristics (eyes, mouth) might improve students' motivation but obstruct their understanding. In the exchange, the contrasting view of participant Ag, who says *"We were not giving the right command"*, can also be observed. In this case, he correctly identified himself as the author of the robot's programming and thus as an agent in determining its behaviour.

Through this dialogue, it can also be observed how the attribution of intention persists in participant G even after being scaffolded by his teacher: *"I think it went mad"* is presented as an alternative hypothesis to human agency.

In Figure 4.13 I present a graphical depiction of the indicators identified through my thematic analysis and the relation between them.

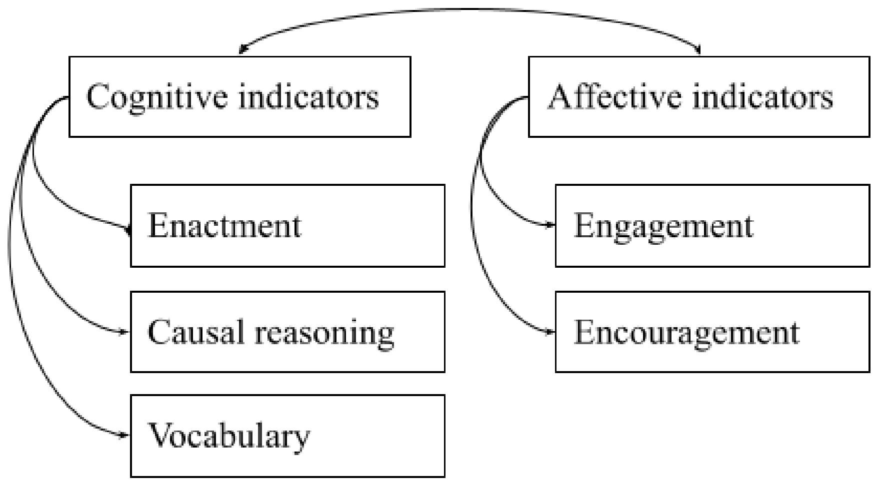


Figure 4.13: Indicators identified in the thematic analysis.

Overall, these findings illuminate the key patterns and insights that emerged from the ethnographic data, offering a deeper understanding of the participants' emergent behaviour and experiences throughout the implementation of the activities in the classroom.

In addition to the observations conducted within the classroom, which produced personal field notes, I conducted post-session interviews with each child in order to explore their understanding of the activities and concepts targeted. The interview protocol is present in appendix A.3.2. These interviews were transcribed and thematically analysed in order to create relevant that also relate to the themes presented in the observations. Table 4.2 presents the extracted codes and examples for each one as extracted from children's post-session interviews.

4.3.3 Observing progression in students' understanding

In the previous sections, I have established the themes that emerged throughout my entire observation of the activities that provide indications of students' understanding. However, in order to have a developmental perspective of the activities, how these indicators change and progress as students engage in the activities with their teachers should also be analysed. It is important to point out that, while I was able to observe patterns in students' cognitive progression, affective indicators were highly variable for individual children throughout the activities, as they tended to relate to students' own personal motivation and interest regarding the subject. In addition, I observed teacher's affective feedback and support were responsive to children's individual needs. As stated, conceptual change is a complex process that encompasses both learning and development (Sloutsky, 2015) and thus affects motivation for the task, which is an essential building block that supports cognitive processes. In table 4.3, I provide the observed trend for conceptual understanding constructed from the empirical observations and the observed progressions for the students, which showcase how the cognitive indicators presented changed when looking at

Table 4.2: Codes extracted from thematic analysis of children's task explanations

Code	**Description**	**Examples**
Use of concept	Children explicitly used one or more of the targeted concepts in their explanations of the activities (i.e explicit mentions of sequences, conditionals or loops in their speech).	*"We were creating a sequence, which is something like... like you need to repeat and repeat."* *"It had a pattern because it repeated over and over... see like red-orange-red-orange-red-orange...* *"A condition is like a promise in that you need to keep it"*
Notion of order	Children made references to or highlighted ordinality in their explanation of the task.	"*it was (a sequence) but see it needs to be in the right order, first orange, then green, then blue and then yellow, and then it repeats*."
Causal speech	Language expresses cause and effect relationships in the tasks.	"*I programmed three times forward and then to the side...that's why I could not reach it (the goal)* ***if*** *I had used two times instead, I would have"* (reached the goal) *"If I repeat then it will do the same all over again"*
Moments of enactment	Children use their body or objects to explain the activity either gesturing, simulating using their body or using other objects as props in their explanations.	"*the robot needed to do like this*" (performs hand motion simulating rotation) *Wait wait wait! Let's say this is the robot and this is the bee...* (she takes a pencil and a doll she has in her hand to pretend one is the robot and the other is the finish line, simulating the activity)
Use of examples	Inclusion of examples or variants to talk about the task.	"*For example you could have a sequence (of numbers) that goes 3-2-1*" *"Like if you have a traffic light, that is like a condition, if there's red you can't go"*
Reference to roles	Children refer, explicitly or implicitly, to their own role in the task (actor, issuer, author).	"***We*** *were the ones programming (the robot)*"
Affectivity	Displays of positive affect or overt expressions of enjoyment.	"*I raised my hand because I really wanted to come*"
Uncertainty	Explicit doubt our uncertainty.	"*I don't know*" or *"I don't remember."*
Disfluencies	Hesitations and/or long pauses in their speech.	"*Uhm...*" (long pause)

the set of activities from a longitudinal perspective. In addition, these results highlight that as students built an understanding of computing concepts, we also observed them connecting and relating what they had learnt with both previous concepts and their everyday life.

Displays of spontaneous enactment in children's explanations of the concept appeared as early as the first sessions (phase 1) for more proficient children. By phase 2 sessions, half of the children had used enactment at least once in the process of explaining the concept. However, I observed that children often resorted to using enactment in moments of high cognitive demand, suggesting enactment appears as a process indicator of the consolidation of the concept.

Lastly, if causal reasoning displays are to be taken into account, my interview data shows that while causal reasoning was not often displayed by children during their explanations of the concepts in the beginning, most of them were using causality by the end of the intervention.

Table 4.3: Observed progression in conceptual understanding per indicator

Indicators	**Phase 1**		**Phase 2**	
	I.	**II.**	**III.**	**IV.**
Enactment	Action-concept congruency is stressed, and enactment is mostly teacher-supported	Students practice the action-concept associations they have learnt	Spontaneous enactment first observed as a problem-solving strategy	Spontaneous enactment becomes part of the student's regular strategies, especially when facing challenges
Causal reasoning	Students rely on trial and error, with few displays of causal reasoning	Students start using causal explanations, but mostly after the fact (e.g., to explain mistakes they made)	Students begin to predict outcomes using causal reasoning (e.g., "If we keep going this way, we won't reach the goal")	Students plan ahead and use causal language to explain outcomes and their reasoning
Vocabulary	Students do not recognise or use the target concept	Students recognise the concept as familiar but cannot define it in their own words (for example, they refer to a "sequence" but can not define it)	Students use the concept and can formulate a basic definition when asked	Students use the concept on their own and use everyday examples to explain it or make connections with previous concepts

Note. Phase 1: Students represent concepts through actions in the physical world; the act of programming is not mediated by a device. In the beginning of this phase, they use their body or physical objects, while later on they represent and solve activities mentally.
Phase 2: Students perform actions that involve the manipulation of pictures or symbols but do not require a formal symbolic language. In the beginning of this phase, they use physical objects such as a floor robot, later on a virtual block-programming environment, and lastly they represent and solve activities mentally.

4.3.4 Phase 3-B: Experimental and microgenetic results

In this section, I present the results from the quantitative and microgenetic analysis in order to a) analyse the effects of my intervention and the possible association with other developmental variables such as executive function skills and spatial language skills and b) explore patterns in children's conceptual understanding trajectories throughout the intervention using a microgenetic design.

Did the intervention have an effect on children's computational thinking scores?

A 2 by 2 mixed-design ANOVA (Group condition: treatment vs control, and time condition: pre-test vs post-test) was conducted to assess the effect of group and time on the total score for the beginners' computational thinking test (Zapata-Cáceres et al., 2020).

As stated in my data analysis plan, I verified model assumptions were met by analysing the normality of the model's residuals using the Shapiro-Wilk normality test. These results were W = 0.98, with a p-value of 0.49, suggesting that the models' residuals do not differ significantly from a normal distribution. We also tested the homogeneity of variances assumption by conducting Levene's Test, resulting in F=0.09 and p=0.95, suggesting there is no significant difference in the variance across groups. As such, model conditions were met, and I was able to carry out the analysis for the ANOVA model.

Our ANOVA results showed a significant main effect of time, F(1, 27) = 8.79, p = .006, η_G^2 = .031, indicating that total scores changed significantly from pre- to post-test across participants.

The main effect of group was not significant, F(1, 27) = 0.38, p = .541, η_G^2 = .013, suggesting no overall difference in total scores between groups.

The interaction effect between time and group, however, was significant, F(1, 27) = 4.95, p = .035, η_G^2 = .017. This suggests that the change in scores from pre- to post-test differed between groups. In order to further explore this difference and correct for multiple comparisons, I run a post-hoc test of pairwise comparisons using estimated marginal means with Bonferroni correction. These results showed there was no significant difference between pre-test and post-test scores for the control condition (p=0.67), while there was a significant difference for the treatment condition (p<0.01). These results are plotted in Figure 4.3.4.

In order to explore whether language skills and executive function skills were associated with children's CT scores, I conducted a non-parametric correlation test using Spearman's rank-order correlation.

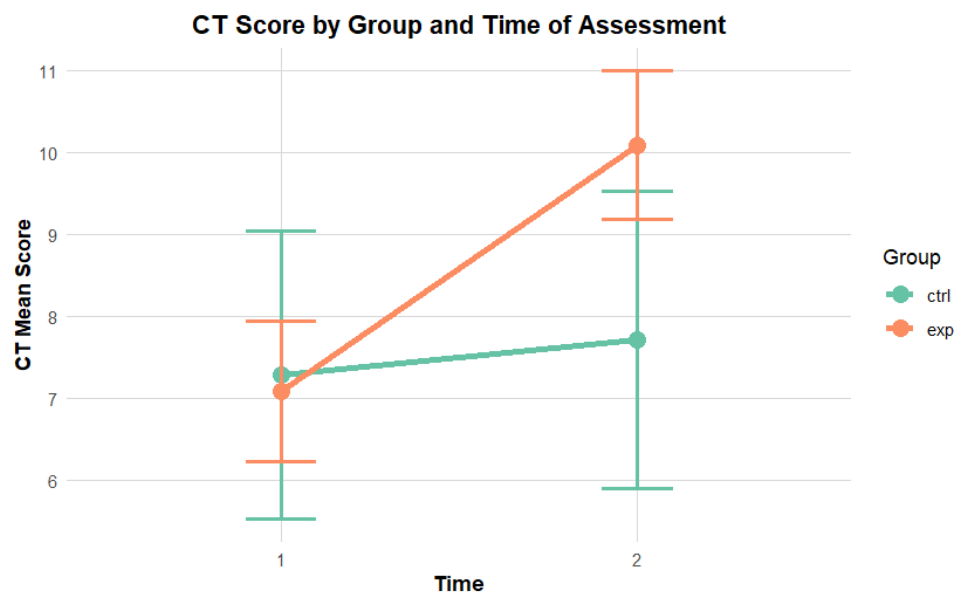


Figure 4.14: Average computational thinking score per group and time of assessment

Is there a relation between executive function, language skills and CT scores?

To examine the association between students' CT scores at baseline and their executive function and language skills, I used Spearman's rank-order correlations. I chose to use a non-parametric analysis given the small sample size and this test's robustness to outliers. 95% confidence intervals for each correlation coefficient were calculated using a bootstrap resampling. This approach provides a more accurate estimate of the sampling variability of the Spearman correlation, given that traditional confidence intervals are not analytically defined for non-parametric correlations.

Results are summarised in table 4.4. Children's CT score was not associated with their executive function skills in the general executive function composite (GEC), their inhibition (ISCI) or flexibility subscales (FI), however, there was a significant negative association between a higher score in BRIEF-P's emergent meta-cognition index (MCI) and lower total computational thinking scores, meaning that having poorer meta-cognitive skills was associated with lower computational thinking. In addition, there was a significant correlation between children's spatial language abilities regarding understanding notions of order as assessed by the ECTE and children's CT.

Table 4.4: Spearman Correlations with CT score at baseline

Variable	ρ	p	95% CI
GEC	-0.34	0.13	[-0.71, 0.11]
ISCI	-0.18	0.43	[-0.65, 0.32]
Fl	0.20	0.39	[-0.29, 0.61]
MCI	-0.57**	0.007	[-0.81, -0.13]
Order	0.53*	.014	[0.08, 0.85]

Note. GEC = General executive function composite; ISCI = Inhibitory Self-control index; Fl = flexibility; MCI = Metacognition Index. *$p < .05$, **$p < .01$.

Microgenetic analysis of children's conceptual understanding trajectories

As stated in chapter 3, participating children took part in a total of 10 early computing sessions (Figure 4.11). In this section, I present the results for the average frequencies for each of the conceptual understanding indicators as described in the previous section.

The microgenetic method provides a detailed framework for capturing developmental changes as they occur, offering unique insights into the processes underlying learning and cognitive shifts (Siegler, 2006). Several methodological considerations must be taken into account for interpreting these results.

In this study, observations were conducted on a weekly basis, reflecting the longer timescale over which children's conceptual understanding is expected to change. While traditional microgenetic designs often involve daily or even continuous data collection, a weekly sampling frequency was considered appropriate for this study as typically conceptual understanding is assessed on even longer time-scales. In addition, weekly data collection reduced the potential for participant fatigue, which is highly relevant when assessing young children.

The conceptual understanding scores in this section were constructed from an exhaustive analysis of children's post-session interviews during the 10-week period. This analysis includes both quantitative and qualitative data. Firstly, thematic analysis was conducted in the post-session interview transcriptions in order to identify the frequency of appearance of several a priori behaviours defined by the results from study 3-A. These codes included: children's use of enactment in ther explanations during interviews, children's explicit use of one or more of the targeted concepts (i.e sequences, repetition/loops, or conditionals/selection), children's references to order or decomposition, children's use of causal tenses, children's explicit statements of uncertainty (i.e when they said "I don't know" or "I don't remember during interviews), children's use of practical examples, and finally children's disfluencies in language (this category included occurrences of long pauses or hesitations). These are defined in section 3. Lastly, I added each child's enactment, explicit use of concepts, examples, order and causality references to create a general conceptual understanding composite score.

Secondly, I analysed quantitative aspects of children's speech in order to explore whether general language skills such as fluency (operationalised as words uttered per minute) and vocabulary (operationalised as total number of different words used throughout the interview) had an impact on their performance and understanding.

Firstly, I examined the frequency of appearance in the indicators for the sessions targeting each of the target concepts (sequences, repetition, selection) controlled by the number of sessions per concept. These results are depicted in figure 4.15

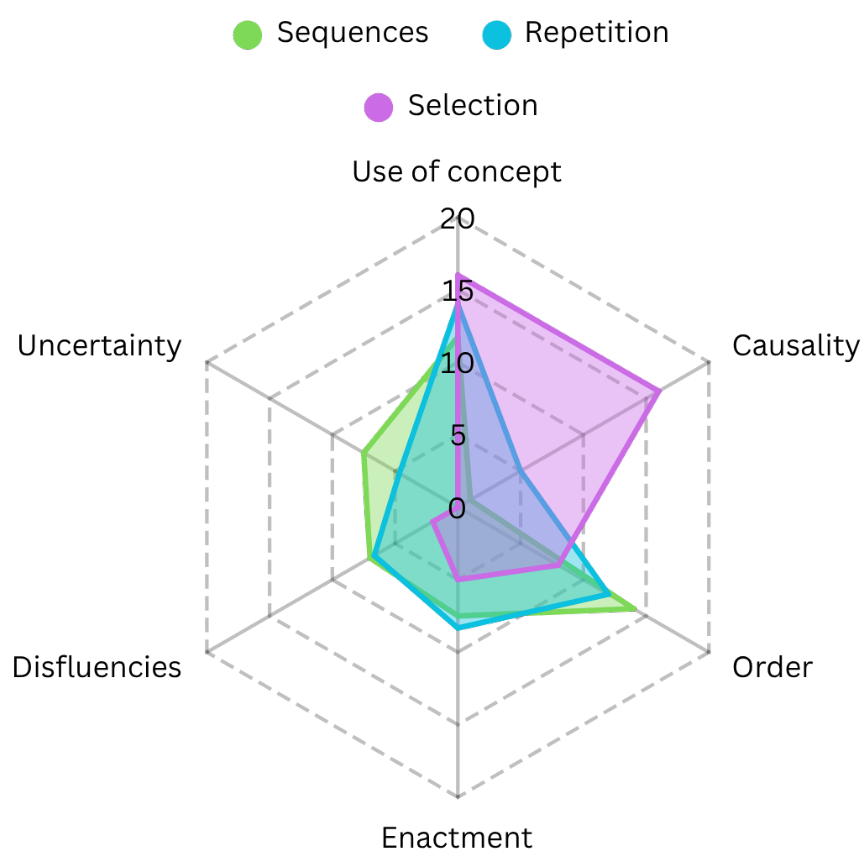


Figure 4.15: Analysis of apparition of indicators per concept controlled by the number of sessions.

Then, I aimed to examine children's trajectory in their overall conceptual understanding score. To visually explore the pattern of behavioural frequency changes over sessions, I fitted a LOESS curve to the data. Given the variability in individual observations and potential nonlinearity in behaviour change over time, the LOESS curve allowed for a visual data-driven exploration of the observations.

I will present my findings for each of the codes, examining the average trajectory for the group of participants.

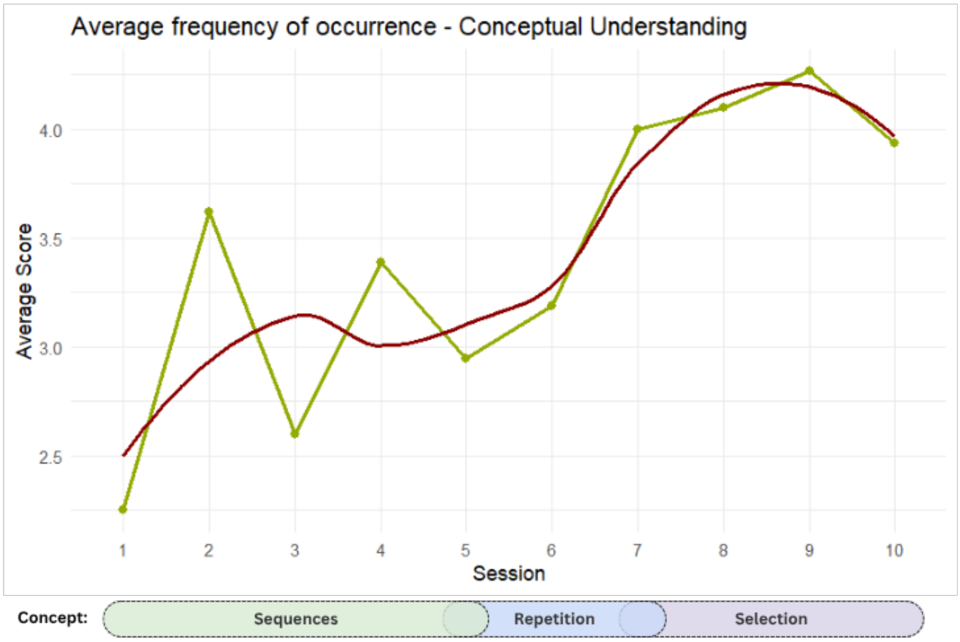


Figure 4.16: Average conceptual understanding score across sessions.

As shown in figure 4.16, children's overall conceptual understanding shows an ascending pattern across sessions, with a higher slope for the sessions targeting the concept of sequencing (sessions 1-5) and higher variability for the concepts of loops (sessions 5-7) and conditionals (sessions 7-10), despite this, we observe children's conceptual understanding scores remain relatively stable in their score from session 5 onwards.

Similarly to their conceptual understanding, when looking at children's frequency in their use of the concepts explicitly (i.e., referring to something as a sequence, loop or conditional) displays an ascending pattern, although with high variability during the first sessions. This is showcased in figure 4.17.

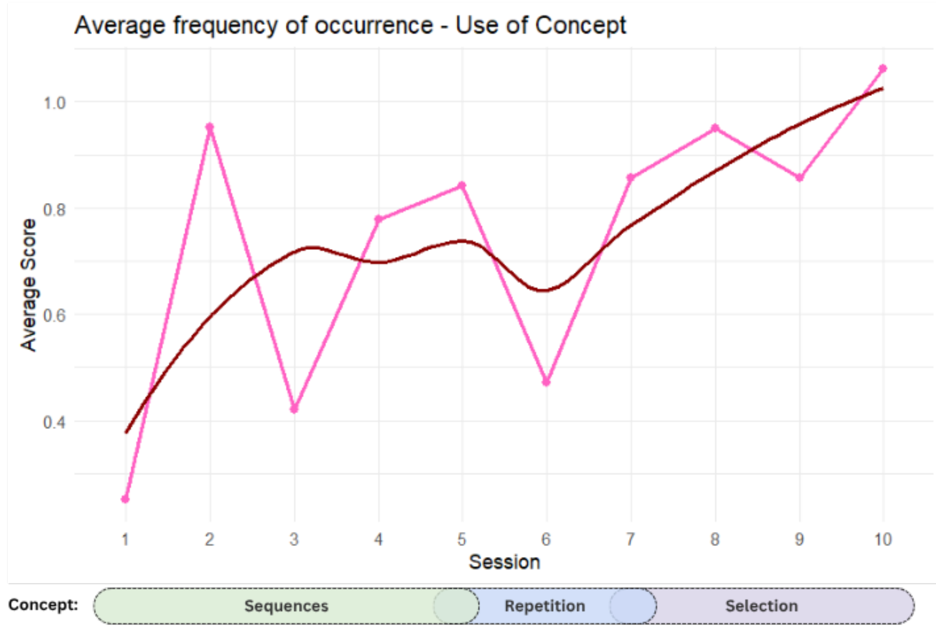


Figure 4.17: Average frequency of explicit conceptual use across sessions.

A similar pattern emerges in children's displays of causal reasoning tenses in their speech. My analysis shows a low-level of use of these types of tenses during the earlier sessions in the intervention, which target the notion of sequencing. On the other hand, a fast increment of causal tenses throughout repetition and conditionally focused activities can be observed, albeit with high variability.

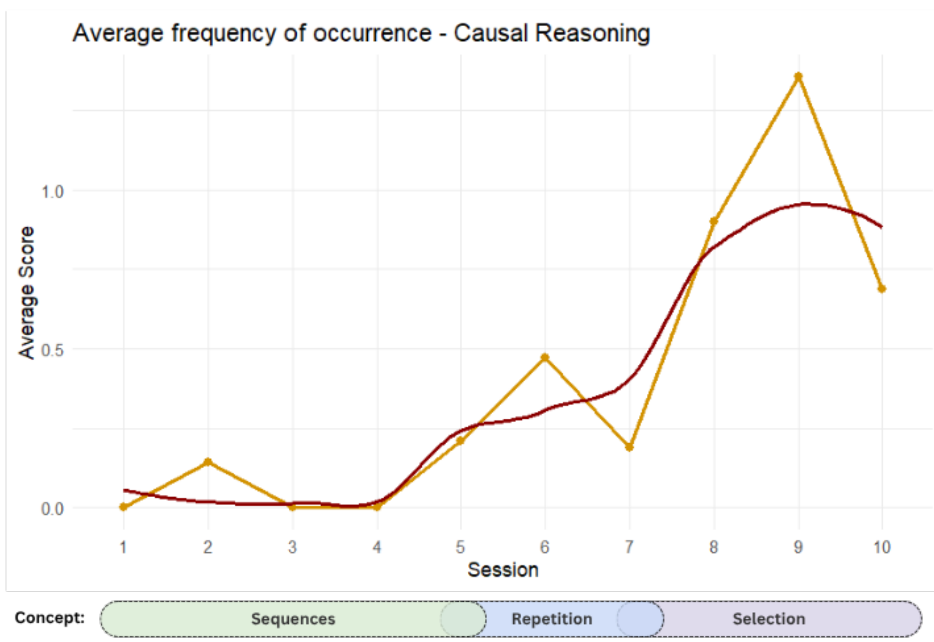


Figure 4.18: Average occurrence of causal speech across sessions.

Strikingly, a somewhat stable at first, then descending pattern is observed for children's references to order or decomposition in their explanations of the concepts. This suggests that children used this notion more often when explaining the concept of sequences than when recounting repetition or conditionals.

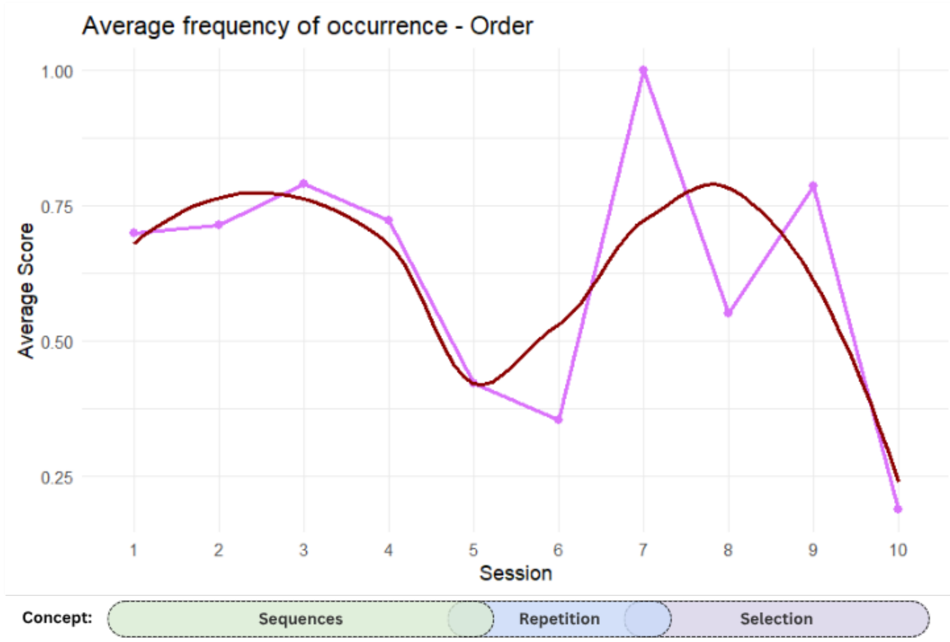


Figure 4.19: Average occurrence of references to order across sessions.

A distinctive pattern emerges in the analysis of the frequency of children's use of enactment for their explanations of the concepts across sessions. It can be observed that children seem to display, on average, an increasing pattern of using enactment during the first half of the intervention (sessions 1-5) and a steady decline during the latter half. Children's use of examples in their explanations and recounts of the activities displayed increases during the first few sessions, with high variability but a stable pattern on average in the latter ones.

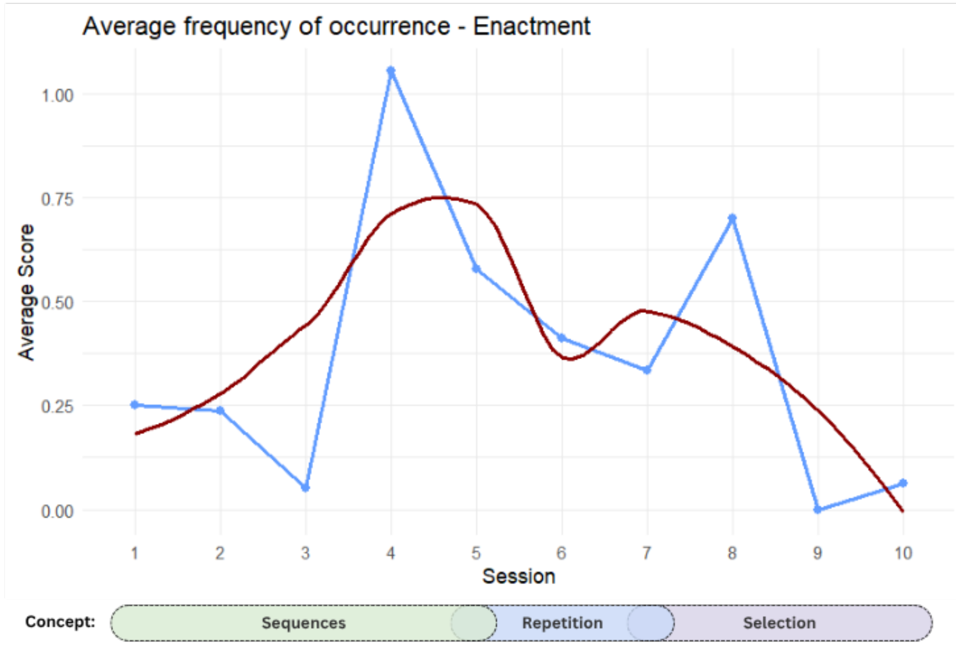


Figure 4.20: Average frequency of moments of enactment.

When looking at what could be considered negative indicators of understanding such as disfluencies and expressions of uncertainty, the data shows that while the presence of disfluencies presents an overall downward trend across sessions, moments of uncertainty (i.e children explicitly replying "I don't know" or "I'm not sure" to the post-session questions) presented variably across the intervention, albeit reaching its highest frequencies during the first two activity sessions.

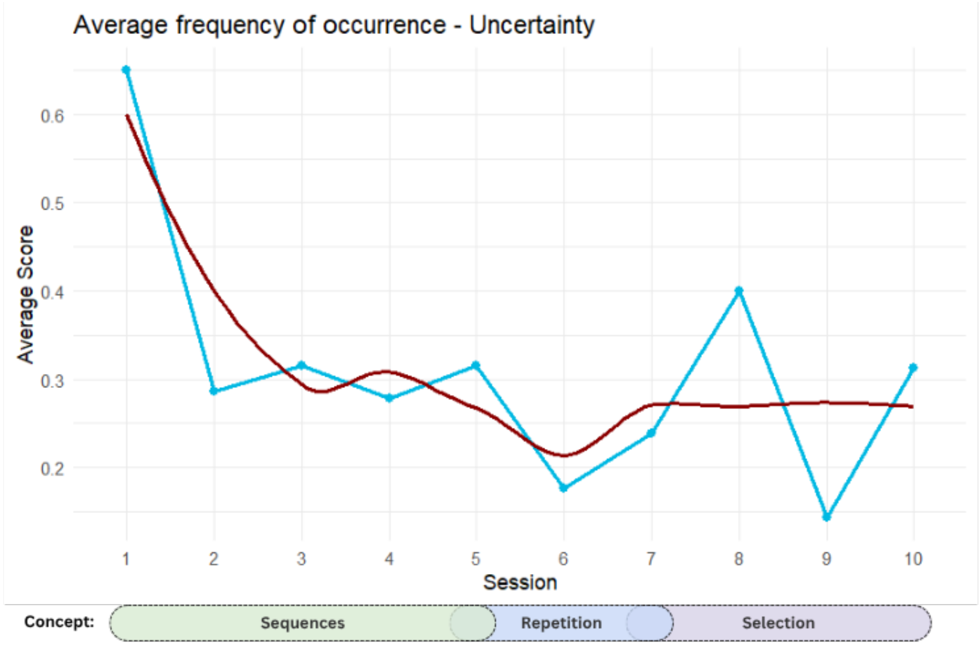


Figure 4.21: Average frequency of uncertainty expressions.

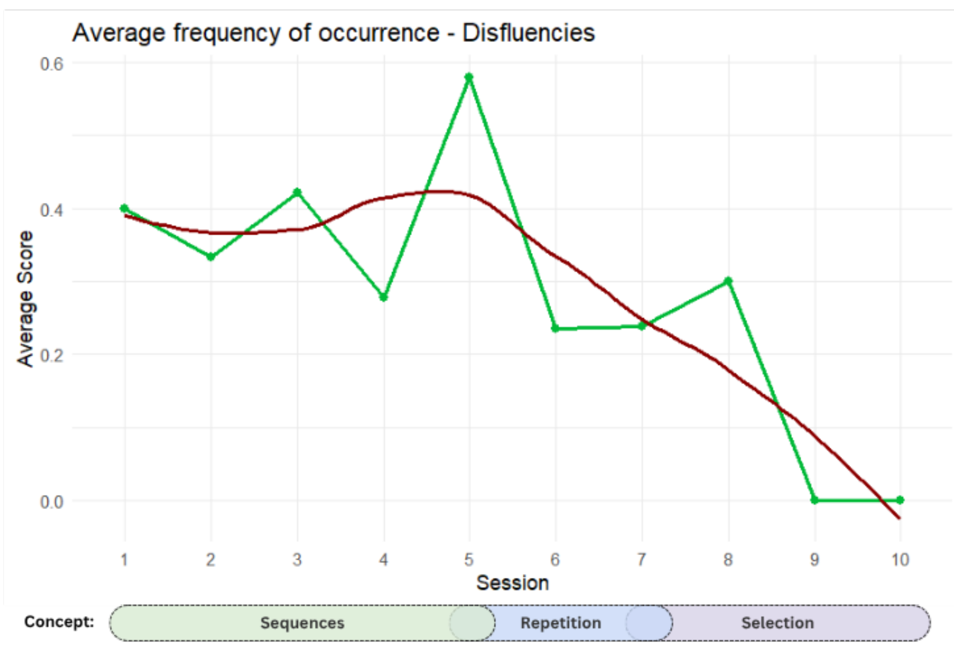


Figure 4.22: Average frequency of disfluencies.

Finally, no distinctive pattern emerges from children's affective references. These presented with high variability, with a few children being frequent displayers of affection and enjoyment towards the sessions and others being consistently more reserved.

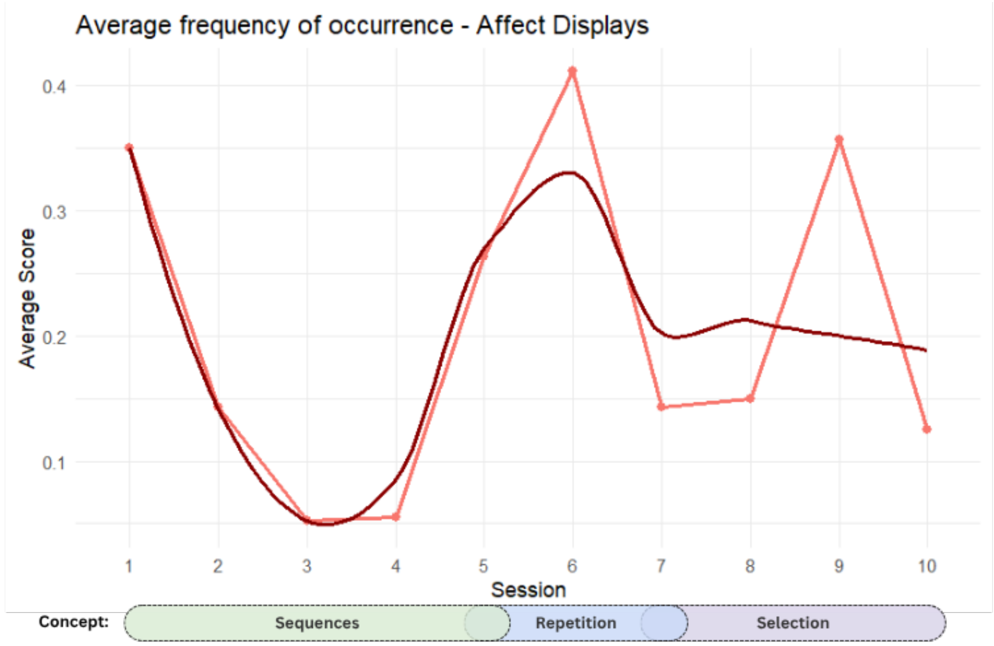


Figure 4.23: Average frequency in positive affectivity across sessions.

Children's enjoyment of the activities

In addition to exploring their performance throughout the activities by examining the indicators of conceptual understanding and assessing any change in computational thinking skills, I also focused on students' reported enjoyment of the sessions. To do this, I incorporated into the post-session interviews a Likert-style question adapted for children as depicted in appendix A.3.2.

Session	Mean Enjoyment	Mean Easiness
1	4.90	4.90
2	5	4.86
3	5	4.95
4	5	4.95
5	5	4.90
6	4.95	5
7	4.90	4.81
8	4.95	4.86
9	5	4.90
10	4.95	4.86

Table 4.5: Child reported session ratings

The results from children's enjoyment and difficulty (above represented by the opposing construct, easiness, as higher scores indicated children found the activity less difficult) showed little variability. It can be observed that children reported very high levels of enjoyment during all the activities, and it was quite rare that they chose a different score, showing a ceiling effect for this measure. The same can be said for difficulty levels, suggesting that child self-reports for these constructs might be unreliable and need to be further explored with a different methodological approach.

Children's procedural outcomes

Children's procedural knowledge was assessed after sessions three, six, eight and ten (last session). Figure 4.24 displays the percentage of children that achieved each category for the procedural assessments (fully achieved, partially achieved or not achieved at all). It can be observed that the majority of children were able to solve the procedural assessments, with the first challenge appearing notoriously easier than the rest.

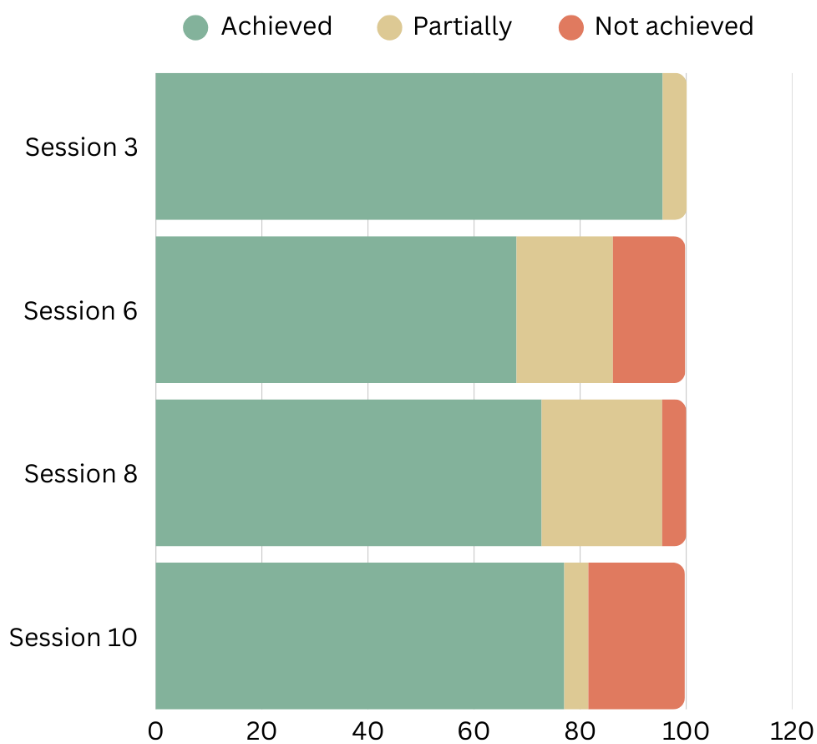


Figure 4.24: Percentage of children achieving each category in post-session procedural tasks

Exploring learners' profiles

Through this analysis, I was able to explore the presence and frequency of the key indicators identified in my thematic analysis. However, I wanted to test whether this set of indicators was useful in identifying distinct learning trajectories for children, not just based on their explanations during post-session interviews but also in relation to their computational thinking scores after the intervention (i.e my objective measure from the BCTT test). Thus, I used children's post-test scores at the computational thinking assessment in order to create a discrete variable of performance levels (high and low performers). Specifically, the median value of the continuous score was calculated across the sample. This median-split approach provides a straightforward method for segmenting the sample into two groups of approximately equal size, allowing for subsequent comparative analyses. Table 4.6 presents the mean frequency of each indicator according to its post-test profile in CT, with significant indicators plotted in figure 4.25.

Table 4.6: Comparison of Indicators Between High and Low CT performers

Variable	**Mean (SD)**		**KW test**
	High performer	**Low performer**	*H (p)*
Conceptual Understanding index	4.14 (1.71)	2.57 (2.16)	31.08(*)
Use of concept	1.05 (0.95)	0.38 (0.73)	28.95(*)
Causal reasoning	0.41 (0.83)	0.30 (0.73)	0.95(NS)
Order	0.57 (0.74)	0.69 (1.01)	0.43(NS)
Enactment	0.43 (0.83)	0.31 (0.57)	0.09(NS)
Affect	0.21 (0.43)	0.18 (0.44)	0.38 (NS)
Uncertainty	0.31 (0.58)	0.26 (0.54)	0.02(NS)
Disfluencies	0.12 (0.35)	0.48 (0.74)	16.17(*)

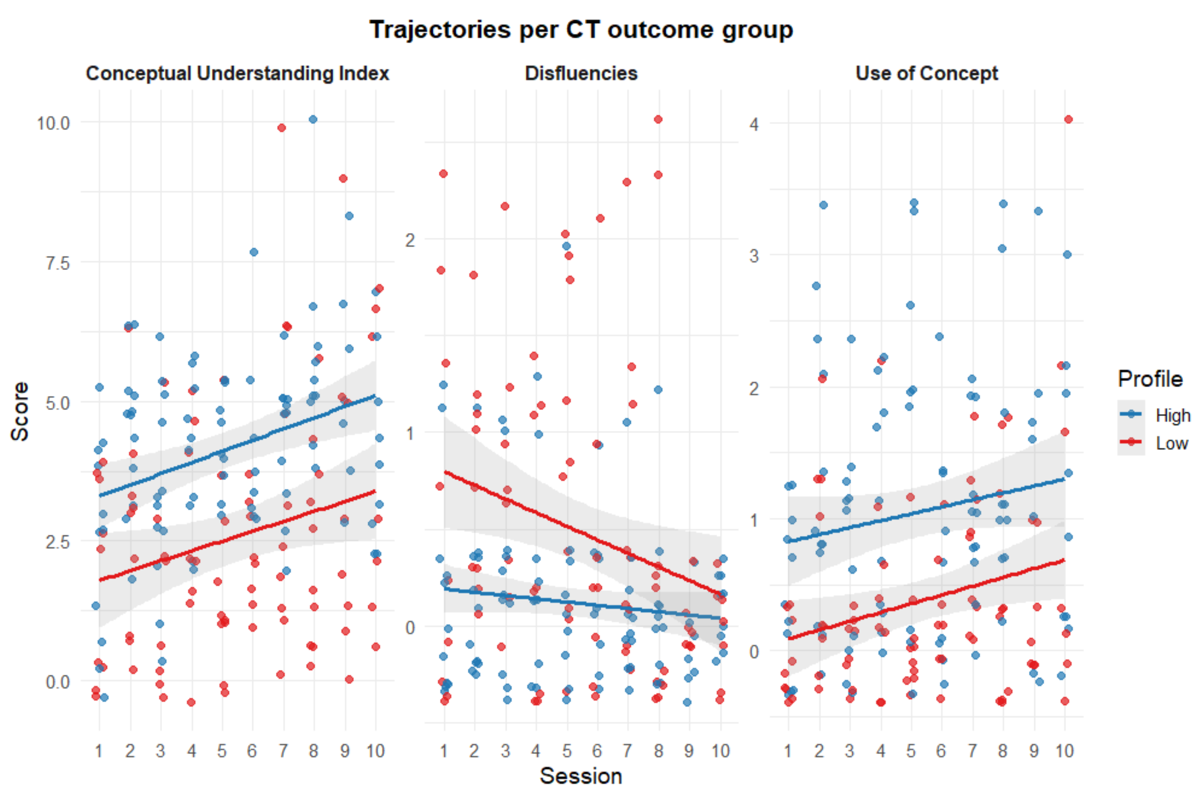


Figure 4.25: Trajectories for high and low CT performers, significant indicators

4.3.5 Phase 3-C: Teachers' perspectives on the implementation

As stated in the methodology section, the present section of the study had the objective of exploring teachers' perceptions regarding the implementation of the activities after their finalisation.

In order to do this, in-depth interviews were carried out with participating teachers. The interview protocol utilised in this part of the study is available in the appendix. The interviews were transcribed verbatim and analysed using thematic analysis. The results for this section are depicted below:

Theme 1, overall value of the intervention, insights into the activities, perception of children's learning:

Part of the first set of questions in my in-depth interview consisted of exploring teachers' perception of the intervention and gathering their insights about the activity after having had the practical, first-hand experience of implementing it and knowing children's response to the instructional strategy. When asked what they would change about the activities, both teachers had a positive response regarding their appropriateness for early years learning:

> *"I found the activities were good, and they adjusted well to the needs of this particular group which sometimes is challenging in terms of behaviour, I think they were motivated because it was new. The questions as well... I would sometimes make questions that for me, they allowed me to assess them in a different way than I usually do, that was good. I felt like I found strengths in some children that I didn't knew they had before. For example (F, boy, 6 year old participant), you could tell he was truly engaged with the topic".*
> — Teacher A.

> *"No, I think they (the activities) are fine, they are in accordance to their age, I saw they (the group of children) were motivated, enjoying themselves... each time we had computing scheduled you could tell they were excited and waiting for that, I remember once we needed to reschedule and they immediately asked what happened, you could tell they loved it.".*
> — Teacher B.

In particular, I was interested in the perceived differences between their previous approach to computing education and the application of the EIFFEL model. It is worth remembering at this point that computing and computational thinking had been mandatory subjects in their curriculum since 2021. Regarding this inquiry, teachers mentioned both similarities and novel aspects of the intervention. For example, teacher B mentioned her previous approach to teaching sequences involved mainly narrative sequences, however she discovered this topic could be tied to computer science.

> *What I usually do is (pause) I work with sequences quite a lot, for example temporal sequences, narrative sequences that they (children) have to organise, we use number lines for maths and there we get to work some sequential ideas as well, you know what comes first, after... I had not worked with these in computer science before but I felt they could take some of that previous knowledge and adapt it to these (the EIFFEL) activities*
> — Teacher B.

Meanwhile, teacher A focused more on highlighting structural aspects of the framework and the contribution of being a novel topic for the classroom:

> *I appreciate that the activities were short, the task was clear... perhaps what was different from other topics was that I got to see them use different words and concepts and some expressed themselves differently. For example, in the activity where they worked in pairs and had to share a sequence with each-other, I was surprised by some of the children's ability to communicate precisely, that's when I could tell that they were enjoying themselves but also improving. I think part of it is bringing something new, new activities, having new faces in the room...*
> — Teacher A.

Next, I turn to teacher's perceptions of student's learning process and whether they could identify any learning benefits. When asked if they noticed changes in children's learning stemming from the activities, the participating teachers had distinct answers. While teacher A saw more improvements in motivational and affective aspects of the activities, teacher B focused more on the use of vocabulary and its links to conceptual understanding. Despite this, both agreed that children benefitted from the activities albeit at their individual paces.

> *I think they all benefitted, some specifically I could tell they were more motivated, some are very keen on the topic. For example (F, boy, 6 year old participant who was mentioned at a different point in the interview) he knew what he was doing, you could tell he was very interested and it allowed me, as his teacher, to find out about interests I did not know he had. I think that helped him gain confidence with his classmates as well. For me, that's what teaching is about, offering different topics to them and supporting them in finding out their interests.*
> — Teacher A.

In addition, the same teacher stressed the importance of including reflexive tasks (metacognitive prompts) within the activities and offering computing tasks that were distinct from others focused on play in order for children to discover new topics of interest.

> *I don't know if you could tell, but they are a very reflexive group (laughs) they enjoyed questioning what they were doing, thinking tasks through again, go backwards a bit... I felt like I could challenge them in something different, we used to work very little with computing concepts, not much. And these new interests they find, it's good that... sometimes they think about computing and all they are interested on is gaming, which is fine, but I think it's our responsibility as teachers to also create interests that go beyond that.*
> — Teacher A.

Furthermore, she stressed structural aspects of the activities as well, pointing to the format of the activities supporting behavioural management.

> *The fact that you are able to start and finish the activity on the same day, it is almost like a workshop, that was useful, they have a clear beginning and a clear end and it helped them focus, also being clear with them (the children) on the objective, for these tasks I would often have to share with them what the goal was and that is something that often gets lost.*
> — Teacher A.

Meanwhile, teacher B focused more on learning gains related to the acquisition of new vocabulary, specifically computing-related vocabulary.

> *They surely talk about sequences more. That is a word that did not exist to them before and now they are able to to put the idea into words. I guess before they did that more automatically but they did not truely relate it to "oh, this is a sequence". I think them having the word for it... at first I would use it and they were not quite there in grasping the idea but now they use it and its clearer to them now, they can describe it.*
> — Teacher B.

Theme 2, Challenges and difficulties identified along the way:

The next theme focuses on teacher's perceived challenges or difficulties throughout the intervention in order to identify possible points of improvement or pitfalls for further practice. When asked about this, both teachers pointed to behavioural control as one of the main challenges during the activities and as a sort of gatekeeping aspect to the learning process. Specifically, teacher B pointed this aspect as a challenging with working with the floor robot in some of the activities:

> *No, the main difficulty they had was more because sometimes they were not paying attention or... for example when working with the robot they needed to wait their*

> *turn to programme it and sometimes I would observe them being anxious, it is hard for them to wait so sometimes they would rush and make mistakes that were not because they did not know how or did not understand, but because they were rushing through it...*
> — Teacher B.

Teacher A also agreed on this aspect and related it specifically to children's learning:

> *I think they were able to make the most of it but sometimes they are a scattered group. I felt that in small groups they worked well and also me knowing them and being able to put the groups together strategically... it is a lovely group but they do have this issue with dispersion and lack of attention, sometimes I feel I have trouble getting to the richer part of the activity because there needs to be time for them to focus on the task. I could tell they would be very participative and outspoken but sometimes I would have liked to reach out more to the inattentive children. I felt they all at some point understood but some took a bit longer than others because of this.*
> — Teacher A.

Moreover, teacher A also pointed to children's meta-cognitive skills and perspective-taking as a specific challenge for them and an aspect to improve in regards to the offered tools:

> *Meta-cognitive questions were good I think because it was difficult for them. I would tell them "Imagine the other person knows nothing about this, they have no information" and that is something that happened with the robot as well, they have trouble taking a different perspective from their own. The tool itself I found a bit frustrating, I think that could have been more intuitive*
> — Teacher A.

In addition, she specifically linked meta-cognitive prompts as a central aspect in promoting children's conceptual understanding, again pointing to behavioural management as a challenge:

> *The biggest issue was getting organised, creating the space for learning, more order... the hardest part for me was that sometimes they thought the concept was simple but they were struggling to understand it. In the beginning for example a lot of their phrasing was circular "a sequence is a sequence", and the challenging part for me was guiding them in a way they understood the concept more deeply and they were able to make that abstract "jump". I think meta-cognition played a fundamental role in that*
> — Teacher A.

When asked about what they would change to the current activity set, teacher B suggested increasing the number of activities working with the floor robot, while teacher A referred to challenges regarding preparation times and specific activities.

> *I would have liked more time for them to familiarise themselves with the robot, I felt my group needed more time there because they were very motivated with it.*
> — Teacher B.

> *Perhaps I felt I lacked the time to prepare properly, in some activities with tangible materials maybe use different resources for them to be motivated with something new. For me, I felt I needed more time. The rest was good but for example in the activity they needed to create a pattern, that one might have been too easy for them.*
> — Teacher A.

Theme 3, Comments on the value of the framework, its progression and concreteness fading as a strategy:

As the last identified theme, I grouped teachers' perceptions regarding specific aspects of the EIFFEL instructional model, specifically the use of concreteness fading as a strategy and its impact on their teaching.

> *I felt the progression helped, they would associate what we were doing was not just one task but they were able to relate and put it into practice, maybe not a first but as they had more activities they would realise how the activities connected. Even in other classroom tasks not related to computing they would sometimes bring up examples from these activities.*
> — Teacher A.

> *I was happy with the progression but I feel level 5 is harder, with some of the tools they become too anxious and sometimes lose track of the process or the concept we were working on. I would help with registering things in the board giving them more time to explore and then focusing on the concept.*
> — Teacher B.

In addition, teacher A reflected on her own position as a teacher regarding computing as a topic and her plans for next year:

> *It was new for me too... it felt like a discovery. I was aware of the topics because of the curriculm and I work in a different school where we have more tools available, I would say I was aware and I try to approach the topic but I felt like I was not as involved as I should. Next year I would love to focus more on computing, perhaps*

introducing some aspects of creation or design, I sometimes feel block-based environment are limited in what they can do, and next year since they already have a foundation and previous knowledge I am keen on trying something shorter focused on designing and using their creativity more. I used to feel computing was sort of a separate space from other classroom activities, for the children as well, but this experience was useful in connecting it and integrating it more, for all of us
— Teacher A.

Chapter 5

Discussion

5.1 Beginning remarks

In this section, I aim to interpret and contextualise the findings of these studies, both in relation to my initial research questions as well as the general research context. In that sense, while my results section was descriptive in nature, here I aim to contextualise these results within the broader spectrum of literature as well as interpret them and provide a frank and substantiated discussion of both its limitations and strengths. I hope that through this, readers achieve an understanding of the topic that is both broad and deep.

This discussion, as the rest of this thesis, is organised in five sections that represent each of the phases presented (systematic literature review, design-based research leading to the creation of the materials and intervention design, ethnographic approach, quantitative and microgenetic analysis and lastly teacher's insights on the intervention).

5.2 Phase 1: Systematic literature review of grounded activities for young children

In the present study, I aimed at identifying grounded approaches (that is, teaching strategies that involve body movements, the use of concrete objects, concreteness fading, or focus specifically on gestures) that involve CS learning aimed at young children, to identify and categorise the reported activities for teaching CS from preschool education to twelve years of age. The first research question that this section aimed to answer was what kind of what I referred to as "grounded approaches" were implemented in research to scaffold young learners of computing. These results showed that researchers implemented a wide variety of these approaches, which include unplugged activities without any use of technology, physical computing objects such as programmable toys or micro-controllers, virtual-based programming environments such as block-based computing or spreadsheet and lastly a mix of two or more of the aforementioned strategies.

Secondly, I aimed to describe which theoretical background researchers were citing and using to inform their research, understand the outcomes of these interventions and describe which (if any) technological tools were being used. Lastly, I aimed to understand what using grounded approaches for teaching computing science meant for designing activities in order to inform follow-up research that will be discussed further on and spans phase 2 of this thesis.

While several of the articles found through the systematic search were able to be classified as grounded approaches to teaching computing, when I examined the theoretical support researchers were citing in order to substantiate their research, very few explicitly cited a grounded cognition perspective as part of their theory. Moreover, I found that even those studies that mentioned grounded cognition referred to general principles and failed to describe how this theory affected their design process for instruction. This was an extremely surprising finding, as my search was specifically targeted using keywords that aimed to find studies related to what could be considered grounded approaches, such as embodied, embedded, enacted, unplugged, etc.

One limitation to this particular endeavour might have to do with the nature of reporting itself: empirical papers often have limited word-counts, and as such, the dedicated space for theory discussion is scarce. Despite this highly practical issue, previous authors in computing education have discussed the role of theory in the field. In 2016, Malmi et al. (2014) examined the theoretical underpinnings of the computing education research presented from 2005 to 2011 in two major journals in the discipline (Transactions of Computing Education and Computer Science Education) and the International Computing Education Research Workshop. Their findings are especially relevant to this research because the authors aimed at identifying theoretical backgrounds that were an integral part of later research rather than mentioned as a general reference in the literature. As such, they expected that the connection between theory and research design, hypothesis, interventions or results was evident to readers. Even though their research was conducted in computing education research in general, and my systematic literature review specifically targeted grounded and action-based approaches to teaching in a specific age group, their findings regarding the use of theory in publications are congruent with mine. Out of a total of 308 papers examined, only 51% (157) presented at least one theory, model or framework. Their most often cited theory was constructivism, which was mentioned fifteen times (Malmi et al., 2014), which is also congruent with my results, as this was my second most-cited theory, even while specifically using keywords connected to grounded cognition theory. However, it is worth mentioning that these results are only comparable in a broad sense, as these studies had different objectives, and my review was much more restricted in terms of exclusion criteria. I chose to classify constructivism and Papert's constructionism separately, while they are pooled in Malmi et al. (2014)'s study. In addition, the number of studies referring to constructivism might be related to the prevalence and strength of the theory in both computing education, related to the work of Papert (Papert, 1980) and education in general. Nearly twenty-five years ago, (Ben-Ari, 2001) referred to constructivism as "the dominant theory of learning" in a review of the theory and computing science education, which points to its relevance throughout the years.

The high number of studies that did not refer to the use of theory to inform their design in both studies is striking and has relevant implications for the directions we take as researchers when making decisions about intervention designs and instruction. Moreover, linking theory to practice is crucial for science itself. As Malmi et al. (2014) points out, being explicit about the use of theory is an integral part of being able to identify relevant, similar work and expanding upon that knowledge.

However, some authors might not completely agree with this stance. In a recent paper, Nelson and Ko (2018) discussed the role of theory for computing education research and argued that theory can enhance but also obtrude on research. They argue that the use of theory might hinder research through diminishing resources for exploration, focusing on domain general learning processes rather than domain-specific ones and possibly creating a publication bias in detriment of design-centred work and theory evaluation. While these are valid concerns, the evidence cited above and the evidence presented in my own literature review point to an under-use of theory-driven research rather than overuse. Thus, my own stance as a researcher coincides with that outlined by Malmi et al. (2014): theory is a key element in guiding design. A large number of studies in my sample (49%) did not report explicitly on a specific learning theory as informing their research or having direct implications in their design of activities. These findings suggest the proposed activities are being determined by factors other than theory.

It is worth also considering the low number of articles that used grounded cognition as a theory in my sample might be related to the fact that grounded cognition is a relatively young field (Barsalou, 2010), although several authors have made efforts to link grounded cognition as a theory of perception and learning with its inherent implications with instructional practice (Shapiro and Stolz, 2019).

I now turn to a different research question in this study, which concerns the practices implemented to teach computing science for young children that could be considered grounded or action-based. When analysing the specific practices which might be linked to grounded cognition theories, I found these studies are mostly dominated by the practice of incorporating concrete materials, often as unplugged computing options, while other strategies such as incorporating whole-body movement into the lessons, analysing gestures or structuring through concreteness fading were used less frequently. As previously mentioned, however, most of the descriptions regarding how theory informed practice were scarce and none of the examined papers delved deeply into specifics on this topic.

Overall, my results in this study point to a gap between theory and practice in the empirical papers on computing education for young children based on grounded approaches, which highlights the need for researchers and practitioners to make more evident how theoretical frameworks inform the design of their activities and how this practice can reflect back to theory (Kallia and Cutts, 2022). The broadness of the interventions I found might be missing important nuances in children's understanding of CS concepts and preventing teachers from creating more developmentally appropriate interventions. As for studies that cited a learning theory, I found many were informed by constructivist and constructionist literature; however, again, the link between this specific learning theory and the instructional practices selected in the studies was unclear. Overall, the impact the theoretical background seemed to have on activity design was negligible. It is imperative that, as CS education researchers, we are able to establish a clear link between theory and practice, as it allows practitioners to design new and innovative practices following similar theoretical principles (Xie et al., 2019).

Some studies might have been left out of my systematic literature review based on being out of the scope of the paper, by being for example, non-empirical or targeting learning in children outside the selected age-range in the criteria. Nonetheless, they still inform my work and are worth mentioning here, for example, in the review by Suh et al. (2020), they examined papers that implemented the use of concreteness fading in instruction design. Out of over 300 papers analysed, however, only 10 of those were in the field of computing. In a recent empirical paper, Trory et al. (2025) used an experimental approach with several conditions in order to contrast primary school children's learning gains in computing using physical and paper-based concreteness fading as well as tablets with augmented reality and a paper-based equivalent (without concreteness fading). Their results showed that even though it was not significant between groups, children using concreteness fading showed higher learning gains. In addition, including concreteness fading in instruction when three stages of representation were included showed significant results, showing consistency with previous work (Trory et al., 2018).

In the analysis of the specific activities designed, there was little correlation between the type of activity and the age of the participants. It was expected that, assuming that older children are more cognitively developed and are thus able to achieve higher levels of abstraction, studies targeting younger children would focus more on concrete materials than those including older children. This finding aligns with the results reported by Falkner et al. (2019) despite studies suggesting different approaches, such as unplugged vs. virtual has different effects on children's learning outcomes depending on their age (Li et al., 2022). It is worth considering that, as interventions tended to be short in duration in the reviewed studies, there was simply no time to build a progression from concrete to abstract materials or actions. A similar aspect was reported by Rich et al. (2017) in her development of learning trajectories for computing, in the fact that in their study they could not correlate children's age to learning goals, as studies varied widely in which concepts were taught at which stage, and there was an over-representation of introductory courses in their sample.

From analysing the targeted concepts and practices in these activities, I found the concepts of sequence, loop, conditionals and algorithms were the most prevalent, with debugging and abstraction as the most often cited practices. Identifying these as the most used concepts present in the studies is relevant as it could be considered an indicator of consensus amongst researchers as to which are the most relevant concepts for computing at an early age.

Finally, I analysed the type of outcome variable the studies focused on and found a large majority focusing on conceptual learning, motivational outcomes or both, with fewer studies assessing specific cognitive skills. I found studies focusing on older children tended to rely more on motivational assessments, which include children's self-reports, and many studies included several types of assessments from more than one category. Despite many studies focusing on conceptual learning, the broadness in the targeted concepts, as previously discussed, did not allow us to make inferences on the benefits of certain activities for specific outcomes. Overall, my analysis of the technologies shows the close association between the use of specific technologies and the activities, suggesting the affordances and allowances of the technological tools might be playing a central role in activity design and outcome variables, rather than theory.

5.2.1 Limitations:

Some limitations are to be acknowledged in the present study. Firstly, an inherent limitation of systematic literature reviews is the prevalence of publication bias in academic research, which has been reported to be at similar levels in computing education as in other fields (Randolph and Bednarik, 2008). As such, it is possible that studies with negative or neutral intervention results are unintentionally excluded from this study based on the fact that they might not have been accepted for publication. Secondly, as stated regarding my question on the links between theory and practice, emphasis on empirical results in publications might have resulted in works that did use a theoretical background to inform their research not having reported it because of space constraints in peer-reviewed journals and conferences. Despite this being a possibility, providing sufficient information regarding theory and explaining its effects on empirical work would be expected to be present, despite the lack of emphasis on these aspects for publication. A third limitation to consider when interpreting the results regarding learning outcomes and utilised technological tools is that, given the specificity of the topic at hand and the relatively low number of available studies, all of the studies that met the inclusion criteria were analysed regardless of their quality and methodological rigour. This was reflected in many of the studies being of relatively short duration and lacking adequate controls.

5.2.2 Key insights and impact:

In this study, I analysed the activities, theoretical background, outcomes and technological tools implemented in empirical research on grounded and action-based approaches to computing education. The main findings have contributed to identifying gaps in the literature, mainly in the existing links between instructional design and the theoretical foundations used by researchers in interventions aimed at early and primary school-aged children. While many of the explored studies did use grounded or action-based approaches to teaching computing to young learners, one of the key insights consists of shedding light on the fact that many did not report on a specific theory supporting their research practice.

In addition, the results point to the activities being heavily influenced by the technological availability and tools' affordances and an overwhelming influence of the role of concrete materials to promote learning with other practices, such as progression-focused activities, which include concreteness fading, gesture analysis or the incorporation of whole-body movement, were reported less frequently. Finally, the explored assessments show that studies have focused on motivational, cognitive and learning outcomes.

5.2.3 How this study guided future research:

The present study was highly influential and useful in my research path as it provided me with a general overview of the field, allowed me to immerse myself in the multiplicity of interventions and approaches targeted at young children from the lens of the theoretical perspectives of grounded cognition theory. In addition, it gave me a clear visualisation of the research gaps as well as the practical reporting gaps (for example, regarding the duration and frequency of the interventions). Part of my personal conclusions from this section of research consists of the need for a stronger connection between theory and instructional design, the need to focus on a specific set of concepts rather than a set of multiple varying concepts and the need to include technology gradually and in low increments in order to study its effects on conceptual understanding.

5.3 Phase 2: Using design-based research to create an intervention based in the EIFFEL model

This phase of the study aimed to answer the question: How can a pedagogical framework based on grounded cognition be designed for its implementation in early years computing classrooms? This study built directly on previous research by Kallia and Cutts (2022), who proposed the initial theoretical model based on the work of Barsalou et al. (2008) and grounded cognition theory in order to promote conceptual understanding during the early years of computing education. This antecedent provided a conceptual model designed to scaffold young children's learning by building on their perceptive and cognitive capacities, the EIFFEL (Enacted Instrumented Formal Framework for Early Learning) model. However, to this date, there has not been an empirical implementation of the model that allowed to contrast its theoretical foundations in the context of real-world classroom settings. In this study, I used design-based research strategies in order to co-design, along with teachers, a strategy to transform the EIFFEL conceptual model in a practice-oriented instructional model.

Following McKenney and Reeves (2018)'s model for designing educational interventions and building on the findings and analysis from study 1, the first step in my design process consisted of summarising the evidence and takeaways from the previous study. Resuming from these findings, which have been discussed in the previous section, the design of the activities started with the following objectives: firstly, since most of the studies in my review targeted a wide variety of concepts and my aim was to promote children's foundational knowledge in computing, this intervention was based on three main concepts, namely sequences, loops (repetition) and conditionals (selection). Each activity in the initial draft for the intervention was thus focused on one main concept. This decision is also supported by previous conceptual work by Rich and collaborators (Rich et al., 2018, 2019b, 2017) focusing on the learning trajectories of single concepts. Secondly, it was observed that while most interventions in study 1 were highly technology-oriented, this study took a minimalistic approach to technology use and was heavily focused on conceptual development. This means that each activity started by introducing the main targeted concept and highlighting the semantic congruency between the task that was being proposed and the main concept, as established by the EIFFEL model (Kallia and Cutts, 2022).

Moreover, this study theoretically connected the EIFFEL model to the semantic dimension of Legitimation Code Theory (Maton, 2013b; Waite et al., 2019) by using semantic waves to structure the lessons within the intervention. While the general use of semantic waves by teachers was checked during observation, further studies could focus on empirically extending this relation. For example, future studies might focus on exploring semantic profiling (Curzon et al., 2020) at different points of the EIFFEL model, which provides opportunities for enacted, instrumented and formal activities.

Previous research on the implementation of computing curricula has highlighted the importance of including teachers' perspectives in instructional design in order to mitigate some common pitfalls of implementation. For example, in a recent review, Liu et al. (2024) pointed out that teachers' limited experience with computing and computational thinking is one of the key issues in its integration into classrooms. Moreover, Sentance (2024) highlights the importance of taking a holistic perspective to teacher professional development that is transformative rather than merely transmissive, thus creating situated and practice-centred development opportunities. This study coincides with this perspective: the intervention ultimately proposed in this thesis used co-design practices involving teachers in order to both scaffold their professional development and support their implementation of the activity. Moreover, this supports my methodological decision of conducting design-based research for the co-design of the activities.

This is especially important considering that the teachers participating in this study were not specialists in computer science but generalist teachers who have had limited training in their academic trajectory in computer science, if any. As such, teachers' background and previous experiences and motivations towards computing inevitably shape not just their self-confidence in applying the intervention, as pointed out by extensive previous research (Dindler et al., 2020; Musaeus et al., 2024; Tuhkala, 2021). This was one of the first themes encountered in the teacher interviews conducted before the implementation of the activities and is a similar situation to that reported in previous studies, where most educational settings include computing through generalist teachers, especially during early ages (Bocconi et al., 2016). In a study examining teachers' perceived challenges in the implementation of computing in the classroom, Yadav et al. (2015) highlighted that generalist teachers, while strong in pedagogical knowledge, do not necessarily have acquired the computing concept knowledge, often having to resort to self-teaching strategies. Moreover, in their study, the authors report that some teachers showcased feelings of loneliness while teaching computing, a similar sentiment to that expressed by the teachers in this study, who reported taking some computing courses online during the COVID-19 pandemic but lacked experience in the topic. It is worth noting that none of the teachers ranked computing as a high-level confidence topic when contrasted with other generalist topics in early years and primary education, such as mathematics, language, art and history. This is relevant since low-confidence for teachers in a specific topic has been correlated with a devaluation of that topic in the enacted curriculum, often times prioritising other things and tending to diminish what teachers feel less proficient at. This data extract in the interview was congruent with arguments pointed out by Larke (2019), where generalist teachers tended to describe computing as a low-priority subject when compared to others in the curriculum.

When asked about their perceptions on the recent changes to the CS curriculum and the proposed instruction model, participating teachers valued highly the role play had in the initial draft of the activities and taking a ludic approach to early years computing. Both play and unplugged activities have a long history in computing education and have been consistently shown to be a valued aspect of instruction design (Bocconi et al., 2016; Critten et al., 2022; Kazimoglu et al., 2012; Liu and Iversen, 2022; Timotheou and Ioannou, 2019; Yu et al., 2023; Yu and Roque, 2019).

Despite this excitement, they stressed their lack of experience as a possible obstacle, with teacher B manifesting that she would like to become more acquainted with the activities. Meanwhile, teacher A described the activities as accessible both in terms of the congruence between her training and the learning goals established by the activities. I consider this especially relevant as she highlighted the value of bringing theory into the design, pointing out her interest in the theory and the connection between the conceptual framework and the didactic and pedagogical decisions.

Based on this feedback from teachers, I decided to make the connection between theory and practice even clearer in the activities by including simple definitions of each concept and clearly identifying the type of activity (enacted or instrumented) and object (physical, virtual or mental) each activity used in order to make the incremental trajectory transparent. Not only is action-concept congruency a central part of the EIFFEL model, as explained by Kallia and Cutts (2022) and thus relevant for teachers to be able to understand and convey this connection to students, but previous research has also shown that offering teachers professional development opportunities rich in content knowledge promotes opportune practices and maintains engagement (Ni et al., 2023). In addition, authors have highlighted the importance to continue teachers' experiences through classroom-based practices, which was encompassed in this study (Mouza et al., 2022).

Similarly, participants were open to introducing concreteness fading in their practices, despite having different levels of familiarity with the concept. While teacher B manifested not being familiar with these notions, teacher A pointed to a less structured use of concreteness fading in the topic of mathematics learning, in line with research conducted in this field for several decades (Abrahamson and Lindgren, 2014; Abrahamson et al., 2020; Fyfe et al., 2014b; Gerofsky, 2015; Tall, 2003). Thus, one of the main changes this intervention introduced in their approach to computing was structure, both within the lessons and across sessions.

Another challenge highlighted in the interview consists of the use of specific devices and the maintenance required for using certain tools. This is part of a long-standing questioning regarding the inclusion of technological devices in schools: as stated by Spector (2001), the conceptual learning goal takes a subsidiary place and explicitly or implicitly, instruction begins to be determined by technology. At the same time, the author points out that the multiplicity of technological devices and tools was exponentially growing (even twenty years ago), and most lacked the empirical evidence to support their use and the investment required from countries to support it. In order to avoid this issue, the present study implemented only unplugged activities accompanied by two specific technologies that have had extensive empirical testing, ScratchJr (Flannery et al., 2013; Portelance et al., 2016; Stamatios, 2024) and BeeBot (Di Lieto et al., 2017; Papadakis et al., 2016; Seckel et al., 2023; Su and Yang, 2023). Specifically, teachers pointed out concerns regarding children possibly breaking tablets or robots if they took them home with them or even misplacing them. Both teachers manifested a need for support in this aspect and valued unplugged activities as a way to surpass these challenges.

As stated in my methodology section, design-based research demands that the investigator occupy a dual role. As a qualitative methodology, it adheres to the notion that, as researchers, we are not neutral to the process and thus allows and values researcher reflexivity in the process. Throughout conducting this section of the study, I was hesitant about where to stop the iterative process of feedback with participating teachers. I considered this part of the study as key in two fundamental reasons: firstly, the activities would lay the groundwork of the intervention and thus would play, to my view, a central role in children's ultimate learning of the concepts, and secondly, as a teacher-led intervention, their participation as co-designers of the activities was integral in ensuring the plausibility of the implementation, their adherence throughout the sessions and their fidelity to their objectives.

In a paper by Larke (2019), the authors referred to teachers as gatekeepers for the successful implementation of the computing curriculum, as they are key facilitators and promoters of the discipline within classrooms. The authors point to the clash between a country-wide policy and teachers' own expertise and experiences in classrooms as the main reason for this difference in goals and approaches. In design-based research and participatory design, however, teachers are not gatekeepers but active constructors of a situated learning environment. Ultimately, the decision to stop the iterative process of feedback with the teachers was not made by me as a researcher but by their own suggestion and enthusiasm to begin implementing the activities. It is worth mentioning as well that time constraints were very important for both participants early on, who pointed out that time for learning and preparing was scarce and thus required that the format of the activities clearly highlighted its main points. These concerns have also been previously reported in educational research, as preparation and professional development time is often scarce (Bubb and Earley, 2013; Villegas-Reimers et al., 2003) in educational contexts where teachers are in high demand, often rely on multi-employment and are in charge of students with variable needs (Lo, 2021).

5.3.1 Limitations:

Limitations and interpretative considerations are to be considered at this point. Firstly, since design-based research is a qualitative approach towards intervention design, these results can be considered highly situated in nature and context specific (Barab and Squire, 2016; Weinberg and Stephen, 2002). While this might be considered a limitation from a positivist framework, through a qualitative lens, this aspect of design-based research can also be viewed as a strength: contextualised, situated interventions are tailored to the settings in which they are going to be applied, and this might facilitate their adoption and adherence. The aim of this study is not to generalise the intervention with an aim towards universality, but to promote conceptual understanding in students through available tools and resources, including the teachers who will be applying it in their classrooms. Despite this, both teachers have several years of experience in early years and the first year of primary education and are thus optimal experts to co-design an intervention for their context. This is related to the threat of subjectivity in their contribution. In order to mitigate this, during all encounters I worked to create rapport with the participants and establish open lines of communication in order to procure constructive feedback (Abbe and Brandon, 2013; Waterhouse et al., 2023). Moreover, teachers also had the opportunity to discuss amongst themselves and establish points of agreement, as well as giving space for their creativity in suggesting changes or adaptations for the activities. Lastly, one more limitation to be acknowledged is that the co-design process can be considered restricted by the theory-driven advancement in the initial drafts of the activities that was highly led by me as a researcher. While activities were completely open to be changed, adapted or improved upon, in practice, most of the proposed activities were embraced by teachers in full, with suggested changes being centred in clarity or building knowledge about the framework rather than the inclusion of new activities (Andersen et al., 2015).

5.3.2 Key insights and impact:

The main takeaways for this study are multiple. Firstly, the results highlight the importance of situating the intervention and promoting teachers' participation as active builders of their practice. Throughout the design process, teachers were able to familiarise themselves with grounded cognition theory's main principles, relate them to their practice and reflect on the nature of the proposed activities as well as the content knowledge in computing. For me, on the other hand, it allowed me to familiarise myself with the intervention setting, establishing their expectations regarding the intervention and collaborating with the participants in iteratively improving the activities. In addition, the results highlight the importance of content knowledge and theory for generalist teachers as well as their main concerns regarding timing, structure and technology use. The main contribution of this study is the creation of a set of theory-driven activities based on grounded cognition that were co-designed and discussed by teachers, thus making them highly plausible and adapted to the context of implementation. Moreover, the product is not only the set of activities but also the creation of a possible trajectory for these activities.

5.3.3 How this study guided future research:

The present research was integral for future studies in that it provided a practical instructional framework based on the EIFFEL model that is able to be subjected to empirical testing. Through the generation of the activity set and trajectory with the teachers, I was able to begin the empirical evaluation of the EIFFEL model activities and thus advance towards the assessment phase of the design-based research cycle. In addition, the product of this study has practical implications for future research and practitioners, given that the designed activities and trajectory are available to be implemented and adapted for different contexts.

5.4 Phase 3-A: An ethnographic approach to the computing education classroom, searching for behavioural indicators of understanding

In this study, I used an ethnographic approach in order to capture the situated aspects of the implementation of the activities created in study 2 and identified several relevant indicators of conceptual development through the use of thematic analysis of the ethnographic notes and interview transcriptions.

The first theme was the enactment of certain activities and the role of motor behaviour in scaffolding and reinforcing conceptual understanding. Enactment and movement could be used as a potential tool for conceptual learning, which was at the heart of the hypothesis regarding the

EIFFEL model, as it was one of its theoretical foundations. According to grounded cognition theory, concepts are constructed through the internal mental simulation of physical events happening in a situated manner. This notion has been supported by previous studies. For example, enacted activities have a documented effect in memory: a recent meta-analysis reported a robust effect for the fact that when children conduct a motor activity which represents a word or phrase, this increases retention (Roberts et al., 2022). As previously mentioned, using embodied activities for learning has a long history in mathematics (Abrahamson and Bakker, 2016; Abrahamson et al., 2020), and there has been growing evidence in the last decades that it might have positive effects in scaffolding learning in computing as well (Sung et al., 2017).

The thematic analysis revealed that not only did children use enactment spontaneously, but teachers also implemented embodied metaphors in their explanations of the concepts. Embodied metaphors are expressions that originate from physical experiences and compare a given idea or concept to physical interactions with the world, often materialising in an embodied expression or gesture. In a recent paper, Manches et al. (2020) studied the use of embodied metaphors in university students and found that knowledgeable adult participants often use embodied metaphors in their explanations of computing concepts, which suggests our understanding of computing is, in fact, grounded for subjects with a developed level of understanding. The use of embodiment in computing has mainly been focused on embodied child-computer interaction (Antle, 2013), which involves specifically targeting design features in our use of computational devices in order to scaffold understanding.

Thus, the findings show that young children frequently use enactment in both their learning process and in their explanations of computing concepts during whole-group discussion within their classroom. I observed that children used enactment as a tool more often in situations of high cognitive demand. Particularly for children's use of the floor robot, part of the findings on the use of enactment suggest contradictions between children's theoretical enacted model of how the robot is going to act and its actual behaviour might occur due to the situated characteristics of the device (for example, terrain constraints might affect its trajectory). This idea relates to the concept of a notional machine as described in computing education research (du Boulay, 1986; Fincher et al., 2020b), meaning as the abstract, idealised model that learners construct about how a program executes. Moreover, this idea has been pointed out as particularly relevant for novice learners (Lowe, 2018) such as those in the present study. Thus, future work might focus on how young children construct their notional machines in the context of a grounded cognition-based intervention such as this one and whether the enacted nature of the activities supports this process of abstraction.

In relation to children's predictions regarding their programs, I also identified that children displayed causal reasoning skills throughout the activities, and these were related to their overall performance. Causal reasoning is at the heart of all human cognitive abilities, as it allows us to understand the world around us (Waldmann, 2017) and is at the base of the construction of empirical and scientific knowledge. Theories on causal reasoning have traditionally studied the role of inference and association in making causal connections: researchers agree that inferential reasoning is an effortful process that requires the use of basic cognitive skills such as perception, attention and memory in order to link ideas at the mental representation level. Throughout the activities, children often engaged in inferences about the behaviour of the programmes they were creating. According to Boddez and collaborators (Boddez et al., 2017), one of the tell-tale signs of inferential reasoning is propositional language. Inferences are thus characterised by premises and conclusions that can be empirically evaluated as true or false.

Thus, inferential reasoning is a complex skill that is supported by general executive function abilities (Boddez et al., 2017). Executive function refers to several top-down neuro-cognitive processes needed for regulating thoughts, emotions and goal-oriented behaviour and is regarded as the basis for complex cognition such as problem solving and reasoning (Blair, 2016; Diamond, 2013; Zelazo and Carlson, 2020). I interpret these findings regarding children's use of causal reasoning skills in light of previous research highlighting the role of general cognitive skills in computing and the opportunity to create situated positive feedback loops. As children build their conceptual understanding, existing concepts also scaffold and shape new knowledge (Sloutsky, 2015; Vygotsky, 2012). From the thematic analysis, similar mechanisms might be at play with more general cognitive skills, where higher executive function skills support children's performance in the activities, engaging in these activities also provides an opportunity for practising these relevant skills, thus forming a bidirectional relation (Robins et al., 2019). Previous empirical studies on the association between early computing skills and executive function in children support this notion (Liu, 2024; Robertson et al., 2020).

Moreover, the results pointed to an increase in the use of concept-specific vocabulary, meaning that there was evidence for the activities being successful in scaffolding children's conceptual development in the process of acquiring new lexical labels and using them accordingly. Vocabulary supports cognition and thought, as it enables us, as humans, to communicate our ideas more accurately and complexly (Borghi, 2023; Yang et al., 2021). This is congruent with Slotusky's model of conceptual development (Sloutsky, 2015, 2010; Sloutsky and Fisher, 2004), as the acquisition of specific vocabulary (lexicalisation) was followed by the use of the concepts for inferential processes.

Additionally, vocabulary has been shown to be crucial for academic performance, as it influences other skills such as reading comprehension, writing skills, and verbal communication (Schuth et al., 2017). Recent studies show that children with a larger vocabulary are better equipped to navigate cognitive tasks because they can access more precise and varied words, which allows for clearer and more nuanced thinking (Marchman and Fernald, 2008; Stokes and Klee, 2009), while in turn vocabulary acquisition is supported by working memory capacity (de Abreu et al., 2011). Thus, these results provide a qualitative view which displays how these variables interact complexly in a real-world classroom setting.

The final theme covered the affective and motivational aspects of learning. Engagement and affect play crucial roles in the learning process, significantly influencing how students acquire and retain knowledge (Corno and Mandinach, 1983; Reeve and Tseng, 2011). Moreover, the affective domain is a part of grounded cognition's conceptualisation. Specifically, Barsalou and collaborators highlight affect's role in the social domain of his situated action cycle, which encompasses our notions of agency, social interaction with others and culture (Barsalou, 2020).

Task engagement, an integral part of the results of this theme, is related to both attentional and motivational factors (Zare et al., 2024) while also being regulated by affective aspects inherent to the social dimensions within the classroom, such as receiving encouragement and support, fostering healthy teacher-child relationships and good classroom environments (Shechtman* and Leichtentritt, 2004). My findings highlight the role of affect specifically for maintaining behavioural control, which was present as a prerequisite for task understanding. According to Mandia and collaborators (Mandia et al., 2023), task engagement in a classroom setting is highly embodied and identifiable through eye-gaze, bodily motion, head pose and facial features. This was evident in my ethnographic account and is especially relevant in younger children, whose embodied displays of engagement are more overt than those of adults (Berger et al., 2018; Frischen et al., 2007). Thus, future studies should consider behavioural control and self-regulation's relation to conceptual understanding.

Lastly, these results suggest the attribution of intention to the floor robot as a possible challenge in their development of conceptual understanding. Previous studies have identified this phenomenon: young children have a tendency to anthropomorphise educational robots. Several studies have identified the ages of 3 to 5 years of age as a time of transition in the categorisation of living and non-living things (Goldman et al., 2023; Okanda et al., 2021; Taniguchi and Okanda, 2024). However, this is related to their exposure time to the tool and the presence of more human-like characteristics in the specific device (Goldman and Poulin-Dubois, 2024). The findings from children aged 5 to 7 showed variability: while some children were able to identify the robot as an inanimate device controlled by themselves as intelligent agents, others attributed mental states to the robot, which impacted their ability to solve certain tasks.

Taken together, it is possible that these findings reflect the latter stages of this transition period and further highlight the importance of accounting for the individual developmental characteristics of children when analysing their conceptual development. It is also worth noting that the presence of materials such as robots throughout the activity also had an impact on their overall motivation and excitement for solving the tasks, and thus, I recommend teachers weigh the benefits of using these tools against their possible drawbacks based on their students' characteristics. Studies on children's understanding of their own agency as programmers and their empowerment in computational tasks show that there is a need for activities and curricula to highlight their role as active agents in programming (Odgaard, 2023).

5.4.1 Limitations:

As a qualitative ethnographic study, the aim of this paper is not to create statistical generalisations but to provide situated observations and insights that can inform similar contexts, and thus, I aimed to provide ample description. As such, I do not consider the lack of generalisation a limitation per se but a characteristic of the ethnographic methodological approach.

In the context of classroom ethnography, one of the main limitations reported in the literature is the presence of the researcher in the classroom as a source of disruption that might have an effect on participants' behaviour, where often rapport building is necessary to observe truly natural behaviours (Murchison, 2010). This aspect was less of a concern regarding teachers, as they had previously participated in professional development sessions about the activities and the objectives of the intervention and were thus more acquainted with the researchers' presence. In order to mitigate the sensation of being observed in part of the children, an introductory session during the first activity was held in order to build rapport and try to minimise any discomfort. Moreover, since the observation and interviews took place throughout all the sessions, this allowed enough time for students to become accustomed to the researcher's presence and supported the collection of more naturalistic data.

Another limitation is that since this study took place over a finite period, it could be argued that I might not have captured the full evolution of classroom practices or long-term developmental and learning trajectories. However, it is important to point out that the duration of the activities is within the range of those reported in early computing education research (Ezeamuzie and Leung, 2022), and these results point to the fact that I was able to observe significant changes in the context of conceptual development.

Finally, since the present study used an inductive method in analysing the themes presented in the ethnography, the interpretation of data might be shaped by the researcher's own background, beliefs, and positionality. To maintain reflexivity, I engaged in both self-reflection and peer debriefing along with my supervisor in order to reduce potential bias.

5.4.2 Key insights and impact:

Several key insights are part of this study. Firstly, it was successful in highlighting key themes within the situated learning process of conceptual understanding following an instructional model based on grounded cognition. From a qualitative standpoint, it was possible to identify the behavioural and cognitive aspects observed in promoting young children's conceptual understanding. Further studies aim to conduct a mixed-method exploration by integrating both qualitative and quantitative data in order to contribute to the comprehension of this complex educational research setting.

These findings have important implications for early childhood education and computing teachers, as they offer a set of indicators that can help assess young learners' understanding of key computing concepts in natural classroom settings. Furthermore, these findings provide valuable pedagogical insights to inform and enhance teaching practices.

5.5 Phase 3-B: Quantitative and microgenetic evaluation of the intervention, mapping learning trajectories

This study aimed to test the efficacy of the intervention designed in phase 2 of the study through quantitative and microgenetic methods in order to assess whether a grounded cognition-based educational intervention to promote conceptual understanding in CS was, in fact, effective in scaffolding young learners. As such, my first question consisted of testing the intervention against a validated measure of computational thinking, namely the beginners' computational thinking test (Zapata-Cáceres et al., 2020). In order to do this, a quasi-experimental design was used in which a classroom that did not implement the intervention participated in the study as a passive control, which continued their learning activities as usual without introducing any novel CS activities. Children in the treatment condition received the intervention designed based on the EIFFEL (Kallia and Cutts, 2022) model, and both groups were assessed before beginning the intervention and after finishing it in order to contrast learning gains while controlling for maturation. These results showed a significant interaction of group (control vs. treatment) and time (assessment before and after the intervention) in favour of the treatment condition, suggesting that the intervention had a positive effect on children's computational thinking scores assessed through items of the Beginner's computational thinking test when compared to a business-as-usual control. It is worth noting the characteristics of the intervention in order to compare it to previous experiences.

While there have been previous studies which have been successful in promoting children's computational thinking skills with relatively short-term educational interventions in general (Alonso-García et al., 2024; Sun et al., 2024; Yang et al., 2025) and through unplugged activities in particular (for a meta-analysis see Chen et al. (2023)), this is the first empirical implementation of the EIFFEL model and instructional framework. As such, these results are aligned with previous research using similar strategies and activities Caeli and Yadav (2020); however, the theoretical learning progression from organised concrete action and materials towards increasingly concrete elements in both this axis had not previously been assessed. However, this study was not just interested in assessing children's possible learning gains in computational thinking, but its main focus, aligned with the EIFFEL framework, is to strengthen young learners' conceptual understanding in computing.

While the qualitative exploration of the model and the extraction of behavioural indicators of children's understanding through thematic analysis of transcribed activities and ethnography has been previously discussed in section 5.4, it is worth noting that part of the main challenges of focusing on conceptual understanding was having an ecological way to assess young children's conceptual development that was meaningful and feasible for young learners who are on the beginning stages of the process of perfecting reading and writing autonomously.

As such, this part of the study builds directly on the findings from phase 3-A in the fact that it utilises the behavioural indicators identified through qualitative analysis in order to explore children's conceptual development longitudinally.

Previous research exploring young children's knowledge in computing has mainly used test-based assessments (Grover and Pea, 2013; Román-González et al., 2017; Tran, 2019; Zapata-Cáceres et al., 2020) or rubrics examining students' projects (Moreno-León and Robles, 2015). Other studies have used students' procedural performance in order to infer conceptual development (Meerbaum-Salant et al., 2010; Werner et al., 2012; Yesharim and Ben-Ari, 2018). Even in adults, where tools such as concept inventories can be used to assess learners, teachers have reported difficulty in exploring conceptual knowledge (Caceffo et al., 2016). As is, the approach towards exploring young learners' conceptual understanding taken in the present research is reminiscent of classical approaches in fields such as psychology, such as Piaget's (Piaget et al., 1952) clinical interview, in which he asked questions and prompted children to provide explanations aloud for their reasoning and answers. This decision was not arbitrary, as it is also the method through which conceptual exploration has been classically conducted in the microgenetic tradition (Puche-Navarro and Ossa, 2024). A similar study conducted with children aged 3-11 has also used this interview approach to conceptual development (Martinez et al., 2015), however, in the context of exploring children's decisions during the activities instead of a separate instance of assessment. While this allowed them to qualitatively understand some of the children's reasoning behind their performance in computing activities in the classroom, the authors conclude that some of the answers children provided for elements such as why they committed errors in purpose had to do more with the inherent exploration of the classroom setting and less with not understanding the concept. Considering this, the approach in which the present study explored young children's conceptual learning is both a strength and a limitation. It is a strength in the sense that it provided separate, session-to-session information of children's understanding of three foundational concepts in computing (sequences, loops and conditionals), and was a highly situated assessment that children grew accustomed to. However, it being highly situated can be considered a limitation as it is harder to compare children's answers to those of studies implementing only test-based assessments. Despite this, the focus on conceptual understanding sought to be a distinct contribution of this work, given that, as highlighted in the theoretical background section, few studies have focused specifically on children's conceptual development in computing.

My next analysis and findings consisted of the microgenetic exploration of children's verbal and behavioural indicators of conceptual understanding. The microgenetic method is defined by its focus on process and by the repeated measurement of participants as change occurs. In this sense, this study focused on capturing young learners' conceptual change through a ten-week intervention in which eighteen computing activities were implemented. Firstly, the frequency of appearance of the indicators per concept was examined. This result suggested that not all concepts are created equal and that verbal and behavioural indicators tended to follow differing patterns of appearance depending on the concept that was being targeted. For example, it was confirmed that children used more frequent causal expressions when talking about the concept of conditions, while these expressions were less frequent in their explanations of loops or sequences. Similarly, expressions regarding the importance of order in a procedure were more frequently present in children's explanations of sequences than in their explanations of conditionals. Expressions of uncertainty and disfluencies were more prevalent during the beginning stages of the intervention, which covered the concept of sequences, suggesting that as children advanced in the computing activities, they presented fewer hesitations in their explanations.

I consider this an interesting finding as it suggests the need to explore the concept's own characteristics for teaching and trying to tailor the activity itself to the concept, an aspect highlighted in the EIFFEL framework, where concept-action congruency is a central aspect (Kallia and Cutts, 2022). Previous work in computing education that also took an grounded-embodied perspective to learning supports this notion that conceptual representation is somewhat supported by concept's own characteristics, for example the work of Manches et al. (2020) tried to identify the embodied metaphors that adult learners show when explaining computing concepts and found that distinct gestures were used to describe different concepts, therefore suggesting that embodiment might be a facilitator of representation that is variable between concept and somewhat culturally shared between individuals. The fact that some indicators appear more frequently for certain concepts and not others has relevant implications for practice, as for example, teachers might work on strengthening certain causal vocabulary with pupils, alongside working on computing concepts such as conditionals.

As previously established, children in the treatment condition showed increased computational thinking skills after the intervention when compared to the control group. However, the objective of this section was not just to focus on whether they achieved a higher performance but on how they constructed their understanding through time. It follows then that the next analysis focuses on the frequency of each indicator through time (longitudinal-microgenetic approach), which allowed for identifying trends in the frequency of indicators as well as understanding the learning trajectory followed by students throughout the intervention. When examining the mean frequency of each indicator per session, the results showed that children followed an ascending pattern in their conceptual understanding index, in the number of times they explicitly used one of the targeted concepts during their explanations and in their causal expressions. I will first address the importance of the first two indicators: these results highlight the importance of conceptual learning and specifically vocabulary during children's learning. Previous research has shown a consistently strong connection between children's vocabulary and their academic performance across several subjects (Lin et al., 2021; Schuth et al., 2017; Treffers-Daller and

Milton, 2013). These results point to its specific importance in computer science and the need to give all beginners, but young learners in particular, a strong basis with vocabulary that strengthens their cognitive ability to represent complex notions. Some research exists to support this notion, for example, when examining older children's computational thinking skills correlates, Román-González et al. (2017) found that computational thinking was related not just to problem solving and spatial ability but also to students' verbal skills. In addition, evidence from adults has shown that vocabulary was also a significant predictor of their programming skills (Graafsma et al., 2023).

Surprisingly, a downward pattern emerged when examining children's use of order across the sessions. This might be related to the previously discussed association between the use of order notions during sequence explanations, with more complex activities targeting conditionals in the latter sessions not needing children to recur to this notion as much. Despite this, the correlation results showed that children with higher computational thinking scores at pre-test also displayed better temporal and spatial vocabulary, a test that specifically assessed notions of order through picture-sequences. Taken together, these results regarding order do not allow me to infer its relevance throughout the activities, but do point to children relying on notions of order in order to understand the concept of sequences. A previous study by Kazakoff et al. (2013) found an association between children's performance in an educational robotics activity designed to support computational thinking and children's sequencing ability as assessed through a picture-sequence task.

Also surprisingly, I could not find a distinctive pattern in children's affective displays throughout the sessions. Previous research has highlighted the importance of students' affective engagement to support their learning. A limiting aspect of this analysis is that it restricts the frequency of the affective displays to the interview moments, excluding relevant affective moments within the classroom that were conveyed in the discussion for study 3-A that implemented classroom ethnography.

When examining theoretically negative indicators, such as the presence of disfluencies (hesitations) in children's conceptual explanations and their manifestations of doubt and uncertainty (i.e., specifically saying "I do not know this" or "I do not remember this"), a descending pattern was observed. This suggests that, as the intervention progressed, children displayed less uncertainty in their relaying of the concepts. This might be related to their increased conceptual understanding score, as discussed above, but it might also be considered that their self-confidence throughout the intervention is a possible confounding variable that can contribute to the fluidity of their explanations through both knowledge and confidence. It is also worth considering that the activities were designed in order to build upon their previous knowledge, and thus, further research might need to explore how these trajectories continue when children are exposed to novel or more complex concepts in the discipline.

Finally, I must focus on the role of enactment for children's understanding and its progression. While grounded cognition theory suggests enactment contributes to understanding (Barsalou, 2015; Barsalou et al., 2008), the empirical trajectory from my data did not show an ascending pattern but a variable one, ascending during the first half of the intervention and descending later on. Initially, I expected children to use enactment more often when that week's activities were enacted in nature, while this was not necessarily the case for all enacted activities. This particular result seems to be more aligned with work by Novack and Goldin-Meadow (2015), suggesting that enactment is used as a tool when children and novice learners are constructing their understanding, yet it is left behind when children gain more knowledge on the concepts. As the intervention was summative, meaning that children were expected to create links between sequences, loops and conditionals incrementally, this pattern is consistent with children who begin to abandon enactment as a scaffold to support their conceptual understanding.

Next, I presented results from comparing the frequency of the indicators for high and low-performing CT children. These results showed that high-performing children in a test-based computational thinking measure displayed significantly more conceptual understanding, used the concepts more frequently and presented fewer disfluencies than their low-performing counterparts. While promising, these results allow us to think of behavioural indicators that contribute to specific learners' profiles in computing education, while also showing the relation between test-based tasks and children's verbal and behavioural displays of conceptual understanding. It is worth mentioning that for my ad-hoc assessment of procedural abilities throughout the sessions, most children were able to successfully complete the tasks, even when their conceptual understanding was being constructed. Both of these results point to a need to focus specifically on conceptual understanding indicators' contribution towards more general skills, such as computational thinking, rather than just focusing on procedural tasks.

5.5.1 Limitations:

Several limitations are to be acknowledged for this phase of the study. Firstly, the relatively small sample size makes quantitative generalisation difficult. While all regards were taken regarding the analytical decisions for the data, ensuring that assumptions were met, the small sample size prevented more complex statistical analysis that might be warranted for future studies, such as hierarchical models. Despite the sample size, model assumptions for ANOVA were assessed and met, and non-parametric analyses were utilised if needed. Regarding generalisation, while this is an objective of quantitative analysis, capturing variability has been an integral part of the microgenetic method and thus a part of the objectives for this section was describing empirical ecological trajectories.

Secondly, the length of the intervention must also be considered. During this study, I was aware that frequency was an important part in learning and thus during the design of the intervention in phase 2, teachers co-designed a schedule that was feasible for them, the institution and participating children. As the study had the aim of exploring the empirical learning trajectories of children, it was considered that ten sessions were sufficient time. However, future studies might explore how these trajectories might behave for longer interventions. Despite this, it is worth mentioning that this intervention is on the longer end of the spectrum if the previous research explored during phase 1 and the data reported in figure 4.2 is to be considered.

In order to account for some of the affective aspects of the intervention, I not only coded children's affective displays during post-session interviews but also included Likert-style difficulty and enjoyment questions. These results showed a ceiling effect, where children displayed very little variability in their choices across sessions, pointing to invariably high levels of enjoyment and low levels of task difficulty. While this might be interpreted as a positive result if it is considered that children maintained their engagement, it must also be considered that the Likert-style questions were unsuccessful for assessing children's true enjoyment and difficulty during the task. This style of question is often used in research with young children (Hall et al., 2016; Toepoel et al., 2019) and has been shown to be more successful than other formats; however, for this data, children proved highly unlikely to choose any other than the happiest option in the question, creating difficulties in interpreting enjoyment results.

5.5.2 Key insights and impact:

This study was the first empirical approximation to the implementation of the EIFFEL model for conceptual understanding in young learners. As such, it has implications in advancing knowledge regarding the framework and contributing to the body of evidence regarding the use of grounded cognition theory-related approaches for early computer science learning. In addition, it has practical implications in testing and identifying learning trajectories based on the verbal and behavioural indicators of conceptual understanding previously identified in study 3-A. As such, it contributes to my understanding of computer science learning in young children from a developmental perspective, focusing not just on whether children acquire new knowledge but specifically on how, which indicators are more relevant at different points of an intervention, when exploring children's conceptual understanding and how they progress. Furthermore, it has methodological implications in furthering the use of microgenetic designs in computing science education research, which has been shown to be effective in describing progressions but currently lacks sufficient development in this specific field (Kazantzis and Hadjileontiadou, 2021; Sullivan et al., 2015).

5.6 Phase 3-C: Teacher's experiences implementing the model:

In the present section of the study, I thematically analysed teachers' post-intervention interviews in order to identify their perceptions, strengths and challenges throughout the activities. Three main themes were created based on the analysis of the interviews, namely intervention and learning insights, challenges and difficulties and comments on the structure and progression of the activities.

As stressed throughout this thesis, teachers' active participation in the study as the key role through which the intervention was being carried out was an integral part of the success and viability of its implementation. As such, this section of the study was especially valuable as it constituted the final analysis in which their perspectives, impressions and feedback were analysed to create a synthesis of the experience. Teachers' perceptions provide insight not only into what occurs in educational settings, but also into how and why practices are adopted, adapted, or resisted in everyday contexts (Shulman, 1986). As such, teachers' impressions serve as a vital source of experiential knowledge that cannot be fully captured through quantitative measures alone. Previous research has shown that educational interventions that are resisted or misaligned to teacher's values are less likely to be implemented effectively and sustained through time (Fullan, 2016).

More importantly, this part of the study complements the design process and findings obtained in study 2, and aligns with participatory and practitioner-oriented research paradigms that argue for the inclusion of practitioner voice as a means of producing highly situated knowledge.

Firstly, it is worth pointing out that both teachers considered the activities to be developmentally appropriate for young children, with one noting that one of the beginning activities might have been too simple for her group of six-year-old children. This strengthens my approach towards the design of the activities in which, instead of focusing on completely novel tasks, I opted to use familiar, previously reported in the literature tasks that might not differ much from those children did outside of computing (Bers, 2020; Strawhacker and Bers, 2019; Yu and Roque, 2019). Previous research focusing on teachers' perspectives of computing activities in the classroom has also found that teachers are worried about this aspect, specifically, what to teach. In a survey of 115 computing teachers from different levels in the UK, Black et al. (2013) found curriculum to be one of the strongest themes in teachers' perspectives on computing, specifically in focusing on computing as opposed to ICT. This is a striking difference regarding the teachers participating in this thesis, as curricular reform in computer science for mandatory computing in Uruguay included computer science and computational thinking for early childhood in 2021, with it being absent from the curricula up until that point for young learners and only offered in a mandatory way to secondary level students.

Another important aspect brought by the teachers was the intrinsic motivation the activities caused in the students and the relation between affective engagement and fun with learning. Both teachers pointed out that students were highly motivated by the activities and the topic of computing in general, and related that to their learning gains. In particular, teacher A marked a comparison between students' motivation being much higher for computing activities than for any other topics. Their rationales for this are twofold, mainly "novelty" as a distinct aspect of this set of activities that can be attribute to the contextual aspects of curricular reform discussed above and that both of the interviewed teachers had not consistently taught computing to their groups before, as well as the inclusion of technological tools that resemble toys such as the floor robot bee-bot and the playful nature of the activities (Bakala et al., 2021; Bers et al., 2022a; Di Lieto et al., 2017; Yu and Roque, 2019).

Regarding the former point, it is worth pointing out that while both teachers declared not having implemented computing activities before the studies conducted in this thesis, they did associate the notion of sequence in computing and in particular the unplugged strategies used in this context with the use of narrative sequences and picture-sequences task that they had implemented in their classrooms and have also been previously implemented in academic literature in the context of computing (Kazakoff et al., 2013).

Regarding the latter point, this is also congruent with previous findings reported by Black et al. (2013), in which teachers highlighted play based learning and specifically aspects of design, something pointed out by teacher A in this study as part of the themes she would like to target in future years, as integral for children's learning and as an effective teaching strategy for computing. In their study, as in this one, teachers tended to value the use of equipment.

I consider teachers' highlights of fun and motivation as an integral part of learning related to their reported main challenge throughout the activities. Both teachers reported that behavioural control and class management during computing activities were a challenge, as children were often over-excited or inattentive. The relation between children's engagement and their conceptual understanding was an aspect also identified during the ethnographic observation conducted in study 3-A, an aspect that is confirmed and supported by the implemented teachers. Moreover, this aligns with previous findings conducted in a similar environment, a Uruguayan public school, in which children's mean task engagement mediated their learning gains in computational thinking (Gerosa et al., 2022). In addition, behavioural management and difficulties in maintaining children's attention have also been reported in previous teacher-centred studies, for example, in the study conducted by Sentance and Csizmadia (2017).

One striking difference between these interviews and the analysis reported in previous studies is the lack of mention of children's gender as an aspect related to their performance. This omission was surprising as previous studies have reported on the existing gender-gap in computing (Master et al., 2021; Stupurienė et al., 2021; Zdawczyk and Varma, 2023) as well as previous teachers' surveys have highlighted that teachers are worried about the social stereotypes related to computing and the possibility of a gender-imbalance (Black et al., 2013; Sentance and Csizmadia, 2017). The omission in the present study might be related to children's young age, as literature regarding this gap is usually focused on older students (Zdawczyk and Varma, 2023) and research from other male-dominated topics, such as maths, has shown the gap increases as children progress through primary school but is not present at the beginning of it (Martinot et al., 2025).

Another difficulty reported by one of the teachers of the implementation consisted of the lack of preparation time and the perceived necessity for more personal preparation before the activities. This particular challenge is also congruent with previous research, both in the context of computing (Sentance and Csizmadia, 2017) and general education, in which demanding workloads and preparation and marking time have been identified as critical issues in teachers' daily work-life that affect their performance and decrease their well-being (Jomuad et al., 2021; Lagawid, 2024; Wahab et al., 2024).

Lastly, the last theme focused on those aspects related to the structure and elements of the instructional model created in the context of this thesis based on the EIFFEL model for conceptual understanding (Kallia and Cutts, 2022). Several aspects of the instructional model were highlighted by teachers as effective to promote student's understanding, these include the structure of the activities, in which both point to "being able to begin and finish an activity on the same day" and "short activities" as strengths of the implementation, the use of meta-cognitive prompts as an aspect that promoted children's reflection about the activities and (mentioned by one teacher) the reinforcement of specific vocabulary that supported children's understanding of the concepts. These results on teachers' perceptions are aligned with the empirical observations conducted independently by me as the researcher in study 3-A, pointing to teachers supporting the value of the instructional aspects of the intervention as well as the general model to scaffold children's learning. Moreover, both teachers valued the use of concreteness fading

5.6.1 Limitations:

Several limitations are to be considered for this study. Firstly, this study is based on the qualitative analysis of in-depth interviews of the participating teachers and spans only two cases of study. As such, while in this discussion I contrasted these results with studies of larger samples, it was not the objective of this study to generalise these results but to provide rich contextualised insights into the intervention on the part of the teachers (Creswell and Creswell, 2017). Secondly, the study is based on the teacher's report and account of the intervention. As such, this data might be skewed by teachers' recall and subjective interpretations of their experiences, as well as some aspects of social desirability. In order to mitigate this, the confidentiality of the data was stressed during the interviews and efforts were made to establish a good rapport and safe environment for teachers to express both positive and negative aspects of their experience. In addition, data analysis in qualitative research has an interpretative nature (Braun and Clarke, 2021), and thus I must acknowledge there is a possibility my own bias as a researcher could have skewed my interpretation. However, in order to mitigate this, I incorporated verbatim quotes in order to contribute to the transparency of teachers' perspectives during the interviews.

Despite these limitations, the study provides an in-depth understanding of the selected cases and contributes meaningful insights into teachers' subjective experiences during the intervention as well as their personal evaluation of it.

5.6.2 Key insights and impact:

This part of the study focused on teachers' perceptions of the implementation after it was finalised. As such, it provided valuable feedback in understanding teachers' perceived strengths and challenges throughout the activities, which allowed me to identify points of improvement for further studies. For example, based on teachers' perceived lack of preparation time, there might be a need for longer professional development courses that strengthen their self-efficacy and their technological, pedagogical and content knowledge. Furthermore, these results point to teachers valuing several of the structural and instructional aspects designed in the context of this thesis and relating them to children's learning outcomes, thus pointing to practical implications of these results and the benefits of aspects such as focusing on conceptual knowledge, strengthening vocabulary, implementing meta-cognitive prompts and using concreteness fading as an instructional strategy.

Chapter 6

Conclusion

6.1 Conclusion

The previous chapter aimed to present and thoroughly discuss the findings of each of the phases of study that constitute this thesis. In this chapter, I will summarise the main arguments stemming from these findings as well as highlight the methodological and practical implications of this thesis, focusing on its contributions to the interdisciplinary field of computing science education. Next, I focus on future steps for both science communication and future research.

6.1.1 Main findings of this thesis:

The aim of this thesis was to explore the ways in which young children learn and understand fundamental computing concepts. This work was supported theoretically by grounded cognition theory and gathered evidence from computing education, psychology and the learning sciences. The work in this thesis also builds on previous theoretical work on computing education, namely the EIFFEL framework for conceptual understanding in computing developed by (Kallia and Cutts, 2022). Specifically, part of the aim of this thesis was to design a set of activities and an instructional progression based on this theory and empirically evaluate the effectiveness of this framework to promote young children's understanding of sequences, loops and conditionals.

In phase 1, a systematic literature review was conducted in order to identify the use of action-based or grounded approaches (teaching strategies that involve body movements, the use of concrete objects, concreteness fading, or focus specifically on gestures) in computer science interventions aimed at children spanning from preschool to twelve years. In the context of the review, I was able to identify current practices in computing education that could be viewed through the lens of grounded cognition theory and analyse their characteristics, explore the theoretical backgrounds informing this research as well as its outcomes, and analyse the technologies implemented in these studies.

The results from this phase of study allowed me to visualise the variety of instructional approaches implemented in grounded and action-based interventions in computing education, including unplugged activities without the use of technology, physical computing activities with objects such as programmable toys or micro-controllers, virtual based-programming environments such as block-based computing and lastly what I called in my review "mixed approaches", which meant those studies that implemented several of these categories at once. Besides visualising the instructional practices implemented in these studies, I was able to explore which theoretical backgrounds authors were citing as supporting their research in light of these activities.

Three main theories emerged as dominant in the reviewed studies: constructivism (Piaget et al., 1980), constructionism (Papert, 1980) and grounded cognition (Barsalou, 2015; Barsalou et al., 2008). Surprisingly, a majority of the studies did not identify a theory explicitly as informing their instructional practices. These results pointed to a gap between theory and practice in current studies aimed at teaching computing to young children, with a vast diversity of strategies being implemented but a rather small number of theories being cited as background, without sufficient explicit connection between the theory and the activities implemented in the classroom. The results from this phase of research contributed to informing study 2 by providing me with insight into the types of activities implemented and their outcome, whether regarding children's learning, cognition or motivation. In addition, this study highlighted the need to design an instructional approach in which its theoretical connections were clearly identified for teachers.

Thus, phase 2 involved co-designing a set of activities based on the EIFFEL framework along with early childhood and primary educators. The EIFFEL (Kallia and Cutts, 2022) provided a conceptual model designed to scaffold young children's learning by building on their perceptive and cognitive capacities. The main result of this phase of research consisted on producing a set of activities that were co-designed with teachers in order to make the instructional approach taken in the context of this thesis feasible and easily applied in the specific context of early childhood and first years of primary education, developmentally appropriate for young learners and in accordance with previous successful efforts to promote young children's learning of computing.

In addition, the activities were structured following the guidelines established by the EIFFEL model. Moreover, the co-design phases with teachers were successful in both familiarising myself with the educational context of this study as well as involving teachers in the theoretical rationale behind the interventions. Throughout the professional development and co-design sessions, I was able to discuss with teachers the theory of grounded cognition, the EIFFEL model and its implications for practice, such as involving concrete actions and objects and introducing the materials following a specific sequence.

Phase 3A consisted of conducting classroom ethnographic research in order to identify behavioural and verbal indicators of conceptual understanding in the context of computing for young learners. This study allowed me to conduct a deep observation and understand the situated aspects of the implementation, and was used as a source for fieldwork notes and post-session interviews with children that were analysed through thematic analysis (Braun and Clarke, 2021). The results of this study allowed me to identify a set of behavioural and verbal themes emerging from the ethnographic process, namely the use of enactment as a strategy for understanding (Pasquinelli, 2006), the use of causal reasoning vocabulary in children's explanations of the tasks, the emergence of specific vocabulary in respect to the concepts targeted in this study (sequences, loops and conditions) as well as affective indicators of learners that related to children's engagement with the tasks and their availability to learn.

This phase was exploratory in nature, and its main contribution was to identify the dynamic and situated aspects of the intervention that can not be reached through other approaches. Moreover, I was able to identify a set of indicators that can be applied by observers in real-world classrooms and that are highly naturalistic, meaning that they are elements that seem to clue us into the fact that children are in the process of building their conceptual understanding, yet are not restricted by formal testing. Given this, they can eventually be implemented by teachers and researchers as practical tools for documenting and supporting students' emerging understanding during everyday classroom interactions. In addition, this qualitative, ethnographic exploration of the implementation then allowed me to quantify the frequency of these behaviours during post-session interviews, an aspect that was further analysed in phase 3-B through a microgenetic approach.

In this study, the main objective was two-fold: firstly, to test the efficacy of the intervention designed in study 2 through quantitative methods in order to assess whether a grounded cognition-based educational intervention to promote conceptual understanding in CS was, in fact, effective in scaffolding young learners. To do this, I used a quasi-experimental design in which an objective computational thinking assessment was used to test whether young children in the experimental condition improved in their practical CT skills Zapata-Cáceres et al. (2020). These results suggested that the intervention had a positive effect on children's computational thinking scores assessed through items of the Beginner's computational thinking test when compared to a business-as-usual control.

Thus, this points to the intervention co-designed with teachers in phase 2 following the guidelines established by the EIFFEL model, which was successful in scaffolding this group's understanding of computing concepts. To have a more developmental, longitudinal understanding of not just if children increased their learning but how this process happened, I analysed the frequency of the indicators established in phase 3A in children's post-session interviews, in which they were asked to briefly, in their own words, explain the concept and the task they had performed during the computing lessons that day. This allowed me to record how these indicators fluctuated throughout the ten sessions of the activities and analyse any patterns of emergence and attenuation of these indicators throughout the intervention. This microgenetic approach to the analysis provided me with a deeper understanding of the dynamics of learning and allowed me to surpass the restrictions of the classic quasi-experimental approach with a pre-test and post-test that is prevalent in the literature (Gerosa et al., 2023) and, while useful in testing general learning gains, could render invisible changes and patterns within the intervention that are worth investigating. In addition to this, I was able to include an observation of children's procedural outcomes in four sessions throughout the intervention in order to analyse the relation between conceptual and procedural achievement, as well as explore the existence of differing behavioural learning profiles for children with high and low CT scores post-test.

Finally, study 3-C thematically analysed teachers' post-intervention in-depth interviews in order to identify their perceptions, strengths and challenges throughout the activities. Three main themes emerged from this analysis, namely intervention and learning insights, challenges and difficulties and comments on the structure and progression of the activities. These results allowed me to broaden the perspective of the study, in Bronfenbrenner's terms (Bronfenbrenner, 1977, 1979) not just through a micro-systemic perspective but through a meso-systemic perspective in which both children's performance and teachers' views and dispositions towards teaching computing contribute to the overall outcome of the intervention.

6.1.2 Limitations:

While the limitations of each specific study conforming to this thesis were more thoroughly discussed in section 5, general limitations of these findings are acknowledged here. In addition to these, several recommendations for further studies based on the findings of this research are detailed here.

The first general limitation is regarding the scope of this research. These studies focused specifically on the context of early childhood and early primary computing education. Specifically, children participating in this research were between the ages of 5 and 7. As such, the results for this thesis are based on a highly specific population that might not relate to the process of conceptual understanding for older children (for example, novice learners that are in more advanced stages in their education, such as late primary). This is especially relevant as these results need to be interpreted in light of this specific developmental stage, as it was the purpose of this thesis to take into account children's cognitive capabilities in order to harness their potential (Diamond, 2013).

Secondly, another limitation of this research is its small sample size. While from a methodological perspective this is not an impediment for the qualitative and microgenetic analysis of the activities, which focus on in-depth rather than broad exploration of the data, this does limit the generalisability of the quantitative results (Creswell and Creswell, 2017). In order to mitigate this limitation, assumptions in the statistical models implemented in study 3B were thoroughly analysed, and these results are discussed accordingly. Despite this, further studies should aim at achieving a larger sample size in order to have robust results.

In addition, while the use of mixed methods was aimed at capturing several aspects of the phenomenon of conceptual understanding in early computing classrooms, it is inherently impossible to capture all aspects of the process, and thus, my selected methodology might have missed some aspects worth accounting for. For example, some studies in early computing and computational thinking have focused on analysing children's productions, whether through the use of unplugged material or by examining their programmes in block-based programming environments (Moreno-León and Robles, 2015). While children created several different programmes throughout the intervention, registering and analysing these was beyond the scope of this study. As such, further research might consider including this analysis, as it might provide rich information regarding children's learning process.

Thirdly, while the intervention time is on the longer spectrum for reported interventions in computing when considering those reported in study 1, it is possible that children's conceptual understanding trajectories are different if a longer time scale were to be considered. Thus, it would be interesting for future studies to continue to use this longitudinal approach using a longer time-frame (for example, one that spans across different grades) to have a broader perspective of how these trajectories behave at a different scale and targeting other concepts of increasing complexity as children advance in their computing knowledge. As such, this research had the objective of focusing on three fundamental concepts in computing and thus further research might be needed in this line in order to understand children's conceptual development of different concepts (Rich et al., 2018, 2019b). More importantly, as this thesis was focused on children between the 5 to 7-year-old age bracket, the theoretical decision to exclude the formal phase of the EIFFEL model was made. Thus, further studies targeting different age-ranges should expand these results by designing and implementing activities that include all phases of the pedagogical framework.

Lastly, other contextual factors that might be influencing children's conceptual understanding of computing might have been beyond the scope of these studies. For example, I was not able to analyse any aspect of how family dynamics and interests in computing (either support or hindrance) might interact with children's learning and motivation throughout the activities.

6.1.3 Future research directions:

The research presented in this thesis offered several insights into young children's conceptual development during early years computing lessons for the concepts of sequences, repetition and selection. Thankfully, no single research project or thesis will ever be able to exhaust questions in this fertile field. In this context, several new related questions arise in order to expand and complement this thesis's findings.

Firstly, as stated, this thesis focused on three fundamental concepts in computing. This selection was made based on previous literature and allowed me to focus on depth for these concepts rather than a wide exploration of several elements. In this sense, future studies could focus on broadening these findings by focusing on other concepts that are also typically covered in the early years and first years of primary curricula. This was a pattern of exploration also followed by previous theory-based research on learning trajectories such as the work of Rich et al. (2017), who begun the creation of trajectories based on literature with sequences, repetition and conditionals and later expanded these findings into the trajectories of processes such as debugging (Rich et al., 2019a), decomposition (Rich et al., 2018) or concepts such as variables (Rich et al., 2022). In this sense, exploring more concepts empirically would provide rich insights while covering more of the curriculum.

Similarly, it would be interesting for future studies to expand these findings by exploring the children's conceptual understanding trajectories during a longer time-frame. The present study had participants from preschool (5 to 6 years of age) and the first year of primary school (6 to 7 years of age). Given this, following theoretical directions in previous conceptual research (Kallia and Cutts, 2022), the formal stage of the EIFFEL model was not implemented at these ages. Thus, future studies could expand these trajectories by spanning a larger age-range and thus observe the particularities of children's transition between the instrumented and formal stage, as well as any challenges that could arise from it.

Secondly, part of the ethnographic results in this thesis point to the importance of the affective dimension in learning, identifying that children who were engaged with the activities showed better performance and the role of teachers' encouragement on affective displays played a role in maintaining this engagement. Despite this observation, in general, since this thesis focused on students' conceptual understanding, the main indicators of understanding identified were behavioural, verbal and cognitive. Thus, future studies could explore further the relation between the affective aspect of computing for both students' understanding and performance; for example, by including formal assessments of children's self-efficacy and intrinsic motivation for computing. In addition, following a bio-ecological perspective (Bronfenbrenner and Morris, 2007), it would be interesting to explore the relation between teachers' own affective dimensions in computing and their students', and its effects on understanding.

In addition, my findings also pointed to enactment as a factor in conceptual understanding, especially for children who were in the process of consolidating the concept and were not yet able to provide thorough explanations. While I have discussed the relevance of this, it is important to point out that in this study, "enactment" constitutes a group of actions and behaviours that could be analysed more granularly. For example, some studies in adults (Manches et al., 2020) have focused on analysing the role of specific gestures on university students' explanations of computing concepts by using video-recordings, something which could be targeted in future studies with young children.

Another point to be made is that part of the findings of this thesis hint at the existence of learners' profiles with differing trajectories in the first years of computing education. Given this, future studies should focus on exploring the relationship between behavioural and verbal indicators, some based on contributions from grounded cognition, such as their enactment of concepts, and children's learning outcomes in computing. Thus, it would be interesting for future studies to conduct more complex analyses with larger samples (for example, cluster analysis or multilevel modelling) in order to consolidate learners' profiles that might be the basis for efficient targeted interventions.

In addition, given that this thesis aimed at analysing my research context in depth, it is necessary that future studies focus on analysing larger and more culturally and economically diverse samples. Thus, further evidence is needed of the implementation of the EIFFEL model in other cultural settings as well as in the context of disadvantaged classrooms were different challenges and opportunities might be identified.

Considering both the results of this thesis and future research directions, it is clear to me that children's conceptual understanding of computing, especially in the early years of primary and preschool, is a rich field that requires further empirical exploration and analysis. To this end, further intervention studies should be conducted, maintaining the perspective throughout this thesis that it is of utmost importance that, as researchers, we are able to immerse ourselves in our context of study, especially considering the complexity and richness of educational settings. Moreover, it is important to consider all variables as interconnected, thus conducting further studies that consider both students' and teachers' perspectives, and even expanding this view to include the role of institutional cultures and schools' relations with their community.

6.1.4 Research contributions:

As stated, the aim of this thesis was to explore how children's conceptual understanding in computing can be facilitated and scaffolded through a pedagogical and instructional framework based on grounded cognition theory. The research findings commented on above provide evidence for the effectiveness of this approach in supporting young learners, as well as being a feasible approach to implement for early childhood and primary school teachers. The contributions of this research can be summarised in several levels: theoretical, methodological, empirical and practical. I will provide arguments for each of these levels in this section.

Theoretical contributions:

From a theoretical perspective, this research contributes to understanding the intersection between computing education and grounded cognition theories by examining the link between children's learning in computing and the use of embodied and enacted activities, as well as tangible materials and concreteness fading strategies.

As previously stated, the work conducted in this thesis builds on previous theoretical work by Kallia and Cutts (2022), as one of its aims was to extend the EIFFEL framework to include concrete instructional aspects and a co-design, along with participating teachers, a sequence of activities that are based on the model and were later empirically assessed.

This thesis's theoretical contributions are twofold: firstly, it contributed towards expanding the EIFFEL model by integrating established instructional elements such as the use of meta-cognitive prompts and semantic waves to structure lessons. Moreover, Phase 2 of the study contributed elements to both support and extend the EIFFEL framework, considering instructional and situational restraints. In addition, it added valuable insights from teachers into the implementation of the model that enriched my understanding of the theoretical framework and directly contributed to designing the activities for instruction. As this phase of research took place immediately after phase 1, I was able to use the gaps found during the literature review in order to guide the co-design of the activities and create a close relationship between the EIFFEL theoretical framework and the sequence of instruction.

The second theoretical contribution consists of identifying a set of behavioural and verbal indicators that are related to young children's understanding of computing concepts. This is especially relevant as it creates an empirical, situated basis through which we might observe understanding through action in future studies. This enacted perspective of what it means to understand a concept during early years and primary is congruent with grounded cognition views of cognition not merely as an internal state but as situated action (Barsalou, 2003). Importantly, my findings point to behavioural and verbal indicators that are relevant for this specific context of learning computing science for early years.

Methodological contributions:

Another contribution of this study consists of its inherent interdisciplinary nature and developmental perspective. While I have chosen to include this contribution in this subsection because it had direct implications for my methodology, I consider this to be both a theoretical and methodological contribution, as the theoretical perspective taken during this thesis is congruent with the methodological path undertaken.

Methodologically, by focusing on how children go through the process of developing their understanding across sessions, this thesis took a developmental perspective by incorporating longitudinal measures (Overton, 2013). This is in line with previous recommendations in the field, in which there is a need for school interventions based in real-world settings that take into account children's learning processes; and thus allow researchers to visualise change and variability across sessions and not just final results (Blikstein and Moghadam, 2019; Guzdial and du Boulay, 2019). Moreover, this thesis incorporated the use of a microgenetic design for collecting data on children's conceptual understanding, thus allowing for the analysis of variation between sessions.

In addition, the identification of behavioural and verbal indicators of understanding in phase 3-A has methodological implications for future studies, as they serve as the basis for explorations in which a qualitative assessment of children's understanding might be required.

Empirical contributions:

From an empirical perspective, this study constitutes the first experience of implementation of the EIFFEL framework in the context of real-world early childhood and primary classrooms. As such, it directly builds on this previous contribution by highlighting the strengths and limitations of the model as well as guiding future empirical studies.

In addition, these studies contributed to the creation of a co-designed set of activities based on the EIFFEL framework that was supported by teachers' insights into the early childhood and early primary context. As such, this has implications for my own further work as well as possibly other researchers who might be interested in further exploring the relation between instruction and learning from a situated developmental perspective.

Taken together, results from phase 3-A and 3-B of the study highlight the existence of behavioural and verbal indicators that could be explored further through larger and longer interventions in order to have a deeper understanding of these trajectories. Results from phase 3-A contribute to a situated understanding of the implementation by providing detailed ethnographic data. Meanwhile, results from phase 3-B highlight the overall effectiveness of the intervention in improving young children's computational thinking skills when compared to a control group. Furthermore, results from study 3-B focused not only on evaluating the efficacy of the intervention but also on exploring the existence of different learning profiles according to students' trajectories and outcomes.

Thus, this study contributes to initial evidence that learners' individual profiles impact their outcomes in early years computing and sets the basis for creating tailored interventions to scaffold young children's needs. In addition, further empirical studies could explore the trajectories for specific indicators and their relation with a grounded cognition perspective of conceptual development, for example, my results showed that children's use of enactment during computing sessions tended to be more frequent when students were in the process of understanding a concept, but less frequent when their conceptual understanding tended to improve and their overall use of the concept increased. This points to the need to explore further the relation between these indicators in order to identify relevant patterns in children's behaviour that can become key elements for practical observation.

Regarding the contributions in the field of computing education for young learners, this thesis is, to the best of my knowledge, the first to implement ethnographic methods and microgenetic design in order to explore young children's conceptual understanding in computing. Moreover, it sought to have an integral perspective by taking into account teachers' perspectives as well as students' outcomes and learning trajectories. The results presented in the context of this thesis thus provide valuable insights into the intricacies of students' journey towards developing conceptual understanding of three fundamental computing concepts (sequences, repetition and selection).

Practical contributions for teaching:

Lastly, from a practical perspective, these activities have implications for teachers, educators and practitioners, either specifically in the context of computer science or, as was the case in the present thesis, for generalist teachers who include computer science topics in their practice.

One of the primary contributions of this thesis is the co-design and validation with teachers of specific activities and strategies teach computer science, following the principles of grounded cognition theory and the EIFFEL model (Kallia and Cutts, 2022). In the context of this thesis, several activities were designed and structured for teachers, resulting in a teacher handbook with activities as depicted in appendix A.2.2. These activities will be made available for other teachers and practitioners who might be interested in applying this theoretical and instructional framework. Moreover, given that the activities are available in both English and Spanish, they could be applied in a wide variety of locations and contexts.

In addition, professional development sessions were also designed and put into practice in the context of this thesis in order to familiarise participating teachers with the EIFFEL model for conceptual understanding and grounded cognition theory principles. These materials are also available, as teachers' feedback reported that they perceived benefits from the professional development sessions in understanding the rationale behind the intervention, as well as creating connections between their previous practices in the classroom with new activities in computing.

Thus, the feasibility and adaptability of the intervention created is also part of its practical contributions. By detailing and reflecting on the factors that facilitated the implementation in study 3-C, the study highlights the need for theory-driven practice, structured instruction and a clear connection between conceptual content and practice.

Moreover, the design phase included not only the activities but also a proposed sequence for the activities following the enacted and instrumented phases of the EIFFEL model, which was empirically tested with positive results for students' outcomes. Thus, this sequence could be replicated or adapted for future interventions.

Lastly, the behavioural and verbal indicators of conceptual understanding identified also have implications for practice: for example, future work could focus on the creation of observation protocols or assessment rubrics designed for teachers to use these indicators during or after classroom activities and contribute to integral student evaluation practices.

Final remarks:

In this section, I have summarised the main findings and contributions of this thesis, indicated some of the limitations of my findings and outlined plans for future research. Reflecting upon the process of this thesis, several areas of contribution were identified and detailed above, including theoretical, methodological, empirical and practical implications for its implementation in real-world classrooms.

When I consider the broader themes of this research, some implications of my findings become especially relevant in the broader context of computing education research: firstly, the need as researchers to explicitly address the connection between theory and practice, especially in the context of designing interventions and tools targeted for young learners, and, in relation to this, the importance of conceptual knowledge as a building-block for further learning and a predictor of positive learning trajectories. In that sense, one of the most important implications of this research is that it highlights the effectiveness of the EIFFEL model, a framework that specifically highlights the need for action-concept congruency in teaching, that is, that the actions and activities we make have a clear correspondence to the conceptual knowledge guiding the activity.

Secondly, I consider that my results make evident the need to continue implementing mixed-methods research in computing education, considering that it was only through the integration of both quantitative and qualitative data that the rich, situated environment of computing classrooms in the early years can be captured. Thus, acquiring a broad methodological skill-set presents itself as a vital element for computing education researchers.

Thirdly, the inclusion of methods that allowed me to capture processes and changes in children was essential to this thesis, as I was specifically interested in how this process occurred and capturing possible patterns and regularities. Thus, conducting further research that also includes a developmental perspective is part of my future goals.

Lastly, this thesis would not be complete without taking a holistic perspective of the learning process, considering its dynamic aspects and the interactions occurring within the classroom and including teachers' perspectives, agency and feedback into the research process, thus, these results also highlight the importance of trying to consider the ecology of the classroom environment (Bronfenbrenner and Morris, 2007) and its implications for learning, avoiding partial views for complex research environments.

Appendix A

Methodological supplement

A.1 Phase 1:

A.1.1 Specific search terms for systematic literature review

Table A.1: Search terms for ACM Digital Library

Search terms
[[Abstract: grounded] OR [Abstract: embodied] OR [Abstract: embedded] OR [Abstract: enacted] OR [Abstract: extended] OR [Abstract: unplugged] OR [Abstract: "physical computing"]] AND [[Abstract: "computer science"] OR [Abstract: "computational thinking"] OR [Abstract: computing]] AND [Abstract: education] AND [[Abstract: "young children"] OR [Abstract: preschool] OR [Abstract: elementary] OR [Abstract: "young learners"] OR [Abstract: kindergarten] OR [Abstract: primary] OR [Abstract: children]] AND [Publication Date: (01/01/2006 TO 12/31/2022)]

Table A.2: Search terms for IEEE

Search terms
"computational thinking" (((("Abstract":grounded OR "Abstract":embodied OR "Abstract":embedded OR "Abstract":enacted OR "Abstract":extended OR unplugged OR "physical computing") AND ("Abstract":"computer science" OR "Abstract":"computational thinking" OR computing) AND ("Abstract":education) AND ("Abstract": "young children" OR preschool OR elementary OR "young learners" OR kindergarten OR primary OR children))))

Table A.3: Search terms for Scopus

Search terms
ABS ((grounded OR embodied OR embedded OR enacted OR extended OR unplugged OR "physical computing") AND ("computer science" OR "computational thinking" OR computing) AND (education) AND ("young children" OR preschool OR elementary OR "young learners" OR kindergarten OR primary OR children)) AND PUBYEAR > 2005 AND PUBYEAR < 2023 AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar"))

Table A.4: Search terms for ERIC

Search terms
AB (grounded OR embodied OR embedded OR enacted OR extended) AND AB ("computer science" OR "computational thinking" OR computing) AND AB education AND AB ("young children" OR preschool OR elementary OR "young learners" OR kindergarten OR primary OR children)

A.2 Phase 2:

A.2.1 Teacher materials: professional development sessions

EIFFEL:
A pedagogical framework for the design and implementation of early computing activities

What is the EIFFEL model?

Enacted
Instrumented
Formal
Framework for
Early years
Learning

The EIFFEL is a conceptual model designed to facilitate the creation and structure of didactic sequences for computing in the early years.

It is inspired theories on grounded cognition and organised following the notion of concreteness fading

Concepts are key

Conceptual understanding is the main objective in the elaboration of the EIFFEL model. In early computing, children must acquire both procedural knowledge and conceptual understanding.

Highlighting the targeted concepts in each activity is very important

Main organisers in the model

01 Action concreteness fading: Actions are thought of according to their level of abstraction, and could be classified as **enacted, instrumented or symbolic**

02 Object concreteness fading: Objects also differ in their abstraction levels and could be classified as **physical, virtual or mental objects.**

03 Action-concept congruence: there must be a **direct link between the action and the semantic meaning of the learning objective**

1. What is action concreteness fading?

Students might benefit from starting from very concrete actions (those that incorporate bodily movement) before beginning abstract computing activities. **The model guides the actions as:**

Enacted: Physical actions happening in the physical environment, in which the individual is the actor of the activities

Instrumented: Students perform actions in a virtual environment which involve the manipulation of pictures or symbols but do not require a formal symbolic language (i.e they might use a simplified pictorial placeholder instead of constructing their code)

Formal: Students perform symbolic actions in a virtual environment. They are the authors of their programmes and use a specific syntax to create and modify their programmes

2. What is object concreteness fading?

Objects are classified according to their abstraction level too! **The model proposes the following classification to think about object abstraction:**

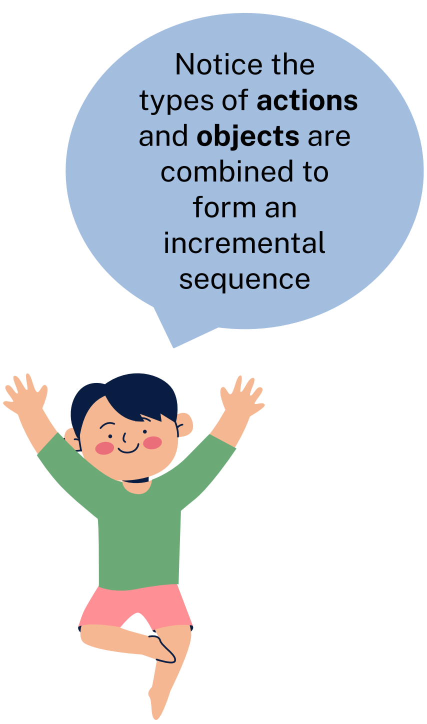
- Physical: Tangible 3D objects which individuals are able to manipulate freely
- Virtual: Intangible objects set in a computer or tablet screen which individuals manipulate through dragging or tapping with their fingers
- Mental: Intangible representations of objects in the physical or virtual world that do not have a 3D or 2D correlate, and in which operations are done through evoking

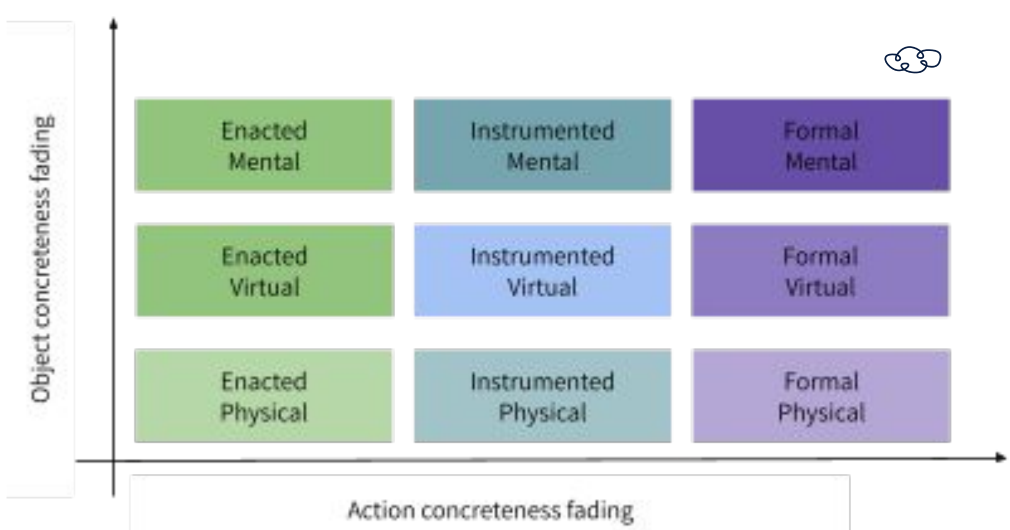
Students go through different roles as they programme

These roles include:

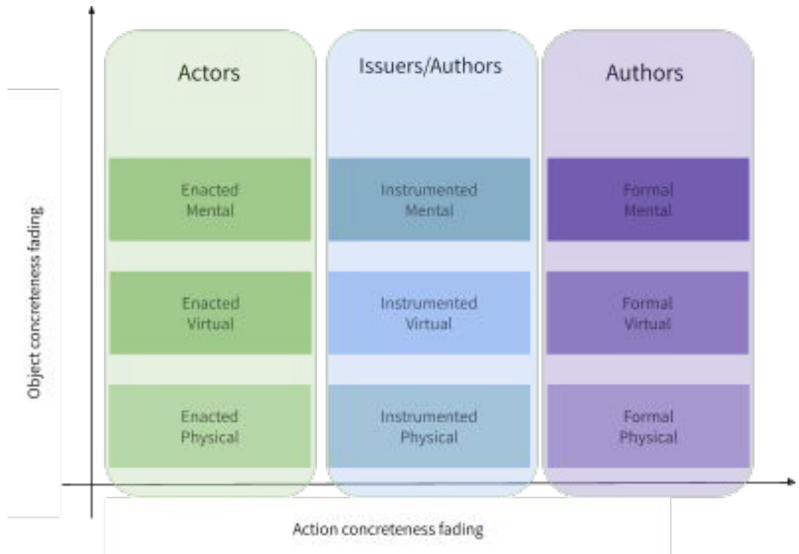
- **Actor:** Children represent their programmes using themselves as objects
- **Issuer:** Children learn to give commands to a machine and see the output of their command in a physical or virtual output
- **Author:** Children use symbolic language to construct their own code and engage in the planning, testing and evaluation of their programmes

Let's see a graphical representation of the model





Children's roles change as they increase their programming skills



Thus far we have:

01

A guideline on how to structure our **learning sequence** according to student's computing skills

02

A conceptual **trajectory** of their abilities

How do we scaffold student learning? Support through metacognitive prompts

- **Metacognition** means "thinking about thinking" and allows us to plan, evaluate our learning goals and adjust our behaviours accordingly.

- Metacognitive prompts can take different shapes, such as helping a student **visualise** a problem in a different way or using timely questions to help them **monitor** their progress

Types of prompts

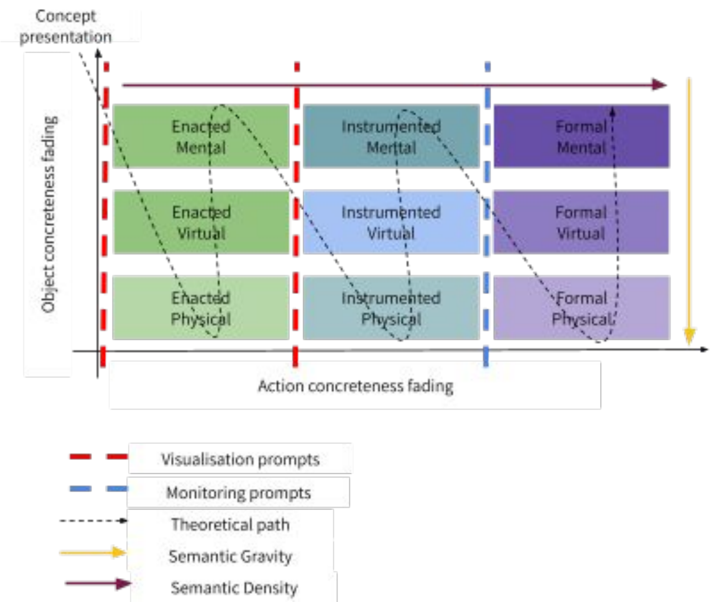
- **Visualisation:** the act of forming a mental image or representing an object or process

- **Monitoring**: the process of self evaluating understanding and learning progress

Both of these have a role in our model!

Prompts support students in the **transition** between phases

Let's imagine the full model thus far:



Quick summary:

- ☑️ **Concreteness fading (action and object)**
- ☑️ **Conceptual congruence**
- ☑️ **Developmental sequence**
- ☑️ **Lesson structure**
- ☑️ **Metacognitive scaffold**

Examples

	Enacted	Instrumented	Formal
Mental objects	Thought exercises that require representing action	Thought exercises in block-based programming (i.e debugging exercises)	Thought exercises in programming (i.e selecting the correct code)
Virtual objects	Virtual reality (VR)	Programming in block based environments (i.e ScratchJr)	Programming in a formal language (i.e Python)
Physical objects	Unplugged and embodied activities	Robotics, tangible programming	

Examples

- Guided drawing - instructor role
- Dance sequence - instructor role

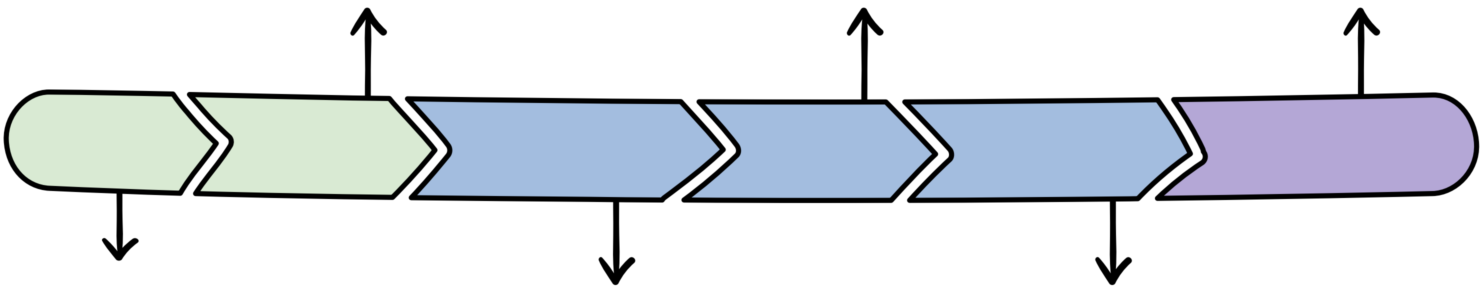
ENACTED MENTAL

- Creating a program in ScratchJr to move a character from point A to B

INSTRUMENTED VIRTUAL

- Programming in a symbolic language

FORMAL VIRTUAL



ENACTED PHYSICAL

- Creating a dance sequence based on daily routines
- Learning about patterns through drawings or legos
- Guided drawings

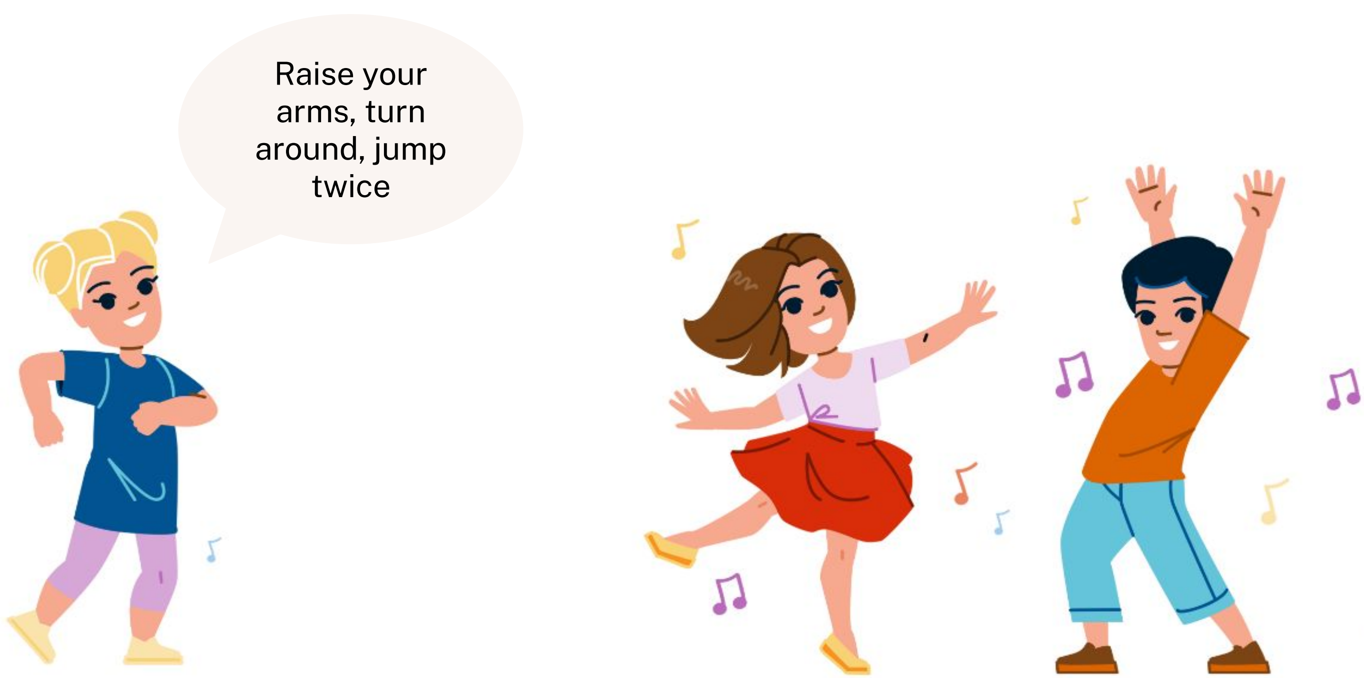
INSTRUMENTED PHYSICAL

- Sequences with Bee Bot, learning to move it through a map

INSTRUMENTED MENTAL

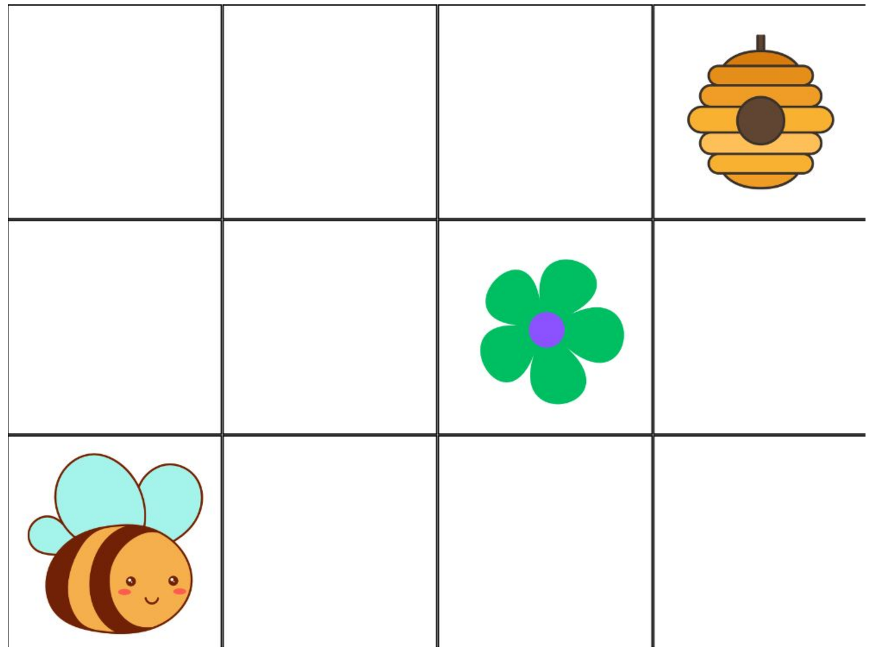
- Debugging
- Block based multiple choice questions

Examples 1



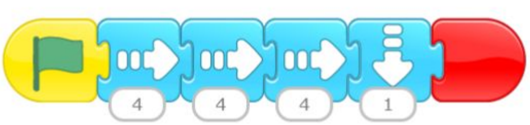
Examples 2

Starting from the bee, programme the robot so that it passes through the flower and reaches the hive



Examples 3

Create a programme so that the character moves from the yellow table to the blue table



Examples 4

Can you create a programme that achieves the same goal but with fewer blocks?

Takeaways for practical activities

Let's say we have a classroom with pupils who are beginners, according to the model, I might want to:

- Center my planned activity around a single, simple concept such as a **sequence** in programming
- Begin with an **enacted** activity, where pupils are the actors of their programme
- Provide **physical** objects to work with
- Use **visualisation** prompts, such as "What did the beginning of my sequence look like?" "How can we represent it?" to wrap up the session

A.2.2 Teacher Handbook:

EARLY YEARS COMPUTING

SEQUENCES

Introduction

This document presents a framework for the design and implementation of computing activities to teach young children fundamental computing concepts. This framework is informed by literature on grounded cognition, specifically on the principles regarding conceptual-action congruence and action concreteness-fading, as described by Kallia and Cutts (2022).

The present framework will focus on three main concepts in computer science education, namely sequences, conditionals, and loops, which there is consensus in the literature regarding their relevance for early steps in computer science (Oda et al., 2021). Specifically, previous findings suggest that most curricula include aspects of algorithms and programming (including control structures) from the early stages (starting in early education). Furthermore, there is evidence suggesting that young children are capable of understanding these concepts from an early age (Bers, 2017).

What is a sequence?

A sequence is the arrangement of instructions or events in a specific order. The notion of order is central to the construction of sequences and involves organising elements systematically to be able to execute them correctly. The formation of simple sequences constitutes the first steps students take in learning programming.

INDEX

SUGGESTED TRAJECTORY

ENACTED ACTIVITIES		Time
I. With physical objects	Everyday sequences	30 min.
	Making patterns	30 min.
	Guided drawing	45 min.
II. With mental objects	Everyday Sequences II	30 min.
	Making patterns II	30 min.
	Guided drawing II	45 min.
INSTRUMENTED ACTIVITIES		**Time**
III. With physical objects	A game of sequences	60 min.
	Sequences with BeeBot	30 min.
IV. With virtual objects	Exploring ScratchJr	60 min.
	First Sequences in ScratchJr	90 min.
V. With mental objects	Programming movement	60 min.

ENACTED ACTIVITIES

Activity	**Everyday sequences**
Action	Enacted
Object	Physical
Student's role	**Actor**
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the given instruction and the behaviour performed.
Materials	None (Optional: music)
Duration	30 minutes
Description of the activity	The teacher will introduce the concept of sequence as a series of ordered steps (5 minutes). We can find sequences in our daily lives, for example, we follow steps when brushing our teeth or preparing our lunch. Today we are going to create our own sequence like a little dance. (20 minutes). Students are taught a rhythmic sequence that represents the steps of their daily routine. To create a sequence, we must first learn what steps make it up. Your first sequence should start with just a few steps (3 or 4), for example: Wake up (stretch your arms), have breakfast (pretend to put food in your mouth), go to school (pretend to walk), go to bed (use your hands as a pillow). Students are asked to verbalise each step as they follow it and create different sequences with different day-to-day routines. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	How many steps did our dance of the day have? Do you remember what the first step of your sequence was? And the last? Would it be the same if we did it in a different order? Could you teach the dance of the day to someone else? Could we invent a new step to add to this dance of the day? What do the different dances/everyday sequences have in common?

Activity	**Making patterns**
Action	Enacted
Object	Physical
Student's role	Actor
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the instruction given and the behaviour performed.
Materials	Beads and thread or coloured stackable bricks
Duration	15-20 minutes
Description of the activity	Sometimes we can spot a sequence in nature. Students will be taught about sequencing using the colours of the rainbow. Teachers will introduce the sequence of colours and ask students to create bracelets by threading the coloured beads in the correct order or creating a rainbow tower by stacking bricks in the right order. Use your whiteboard to help children remember the correct order of colours. In order to simplify the sequence we suggest using: Red, orange, yellow, green, blue, purple.
Metacognitive prompts	How many beads/bricks did your sequence have? What was the first step of your sequence? What about the last? Can you name a colour in the middle of the sequence? Would our bracelet/tower look the same if we did this in a different order?

Activity	**Guided drawing**
Action	Enacted
Object	Physical
Student's role	**Actor**
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the instruction given and the behaviour performed.
Materials	Paper Coloured pencils Templates (see supplementary materials)
Duration	45 minutes
Description of the activity	The teacher will introduce the concept of sequence as a series of ordered steps (5 minutes). The teacher gives a series of instructions to the students to draw the figure on the template. Students cannot see the template, they must only do what the teacher's instructions say. The teacher must give instructions in an orderly manner so that the student follows the sequence of steps to draw the corresponding figure. Ex: 1) I draw a large circle in the middle of the page; 2) divide the circle in half with a horizontal line 3) Inside the circle, at the top right draw another circle, etc. Finally, ask the metacognitIve questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	What do the sequences you have created so far have in common?

Activity	**Everyday sequences II**
Action	Enacted
Object	Mental
Student's role	**Author**
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the instruction given and the behaviour performed.
Materials	Ninguno (Opcional: música)
Duration	30 minutes
Description of the activity	Students must give instructions/sequences to another group of students by teaching them the steps of a dance or rhythmic sequence of a daily routine. The students who lead the dance will have to think about the steps that make up their routine (brushing teeth, hands, making the bed, etc.) and give the correct instructions so that the rest of the group can execute the sequence of steps (the dance). Afterwards the roles will be reversed, those who have given the instructions for the sequence will have to execute it and vice versa. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	How many steps did our dance of the day have? Do you remember what the first step of your sequence was? And the last? Would it be the same if we did it in a different order? Could we invent a new step to add to this dance of the day? What do the different dances/everyday sequences have in common? What similarities and differences are there between the role of actor and that of author? Which is more complex and why?

Activity	**Making patterns II**
Action	Enacted
Object	Mental
Student’s role	**Author**
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the instruction given and the behaviour performed.
Materials	Lego blocks Pattern templates (See supplementary materials)
Duration	45 minutes
Description of the activity	In pairs, one of them will be the one who creates and gives the instructions (Author) and the other will be the one who executes the instructions and builds the figure with the Lego blocks (Actor). The author has to abstract the relevant information from the template, go find the parts he needs and then instruct his partner to build the same part of the template without seeing it. Once you have the necessary material, you give it to your partner. You have to break down the problem into simpler steps and communicate it to your partner so that he or she can build the piece. Ex: Small pieces and large pieces; pieces of different colors; the position of the pieces (above or below, right, left, as many positions to the right...). You must give instructions in an orderly manner, that is, create the algorithm. When all the instructions have been given, evaluate if the partner has made the same pattern as the template. Roles will be changed so that both students experience the role of actor and author. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	What similarities and differences are there between the role of actor and that of author? Which is more complex and why?

Activity	**Guided drawing II**
Action	Enacted
Object	Mental
Student's role	**Author**
Concept	Sequences
Learning goals	- Identify the beginning, intermediate steps, and end of a sequence. - Follow instructions. - Understand the association between the instruction given and the behaviour performed.
Materials	Paper Coloured pencils Templates (see supplementary materials)
Duration	45 minutes
Description of the activity	In pairs, one of them will be the one who gives the instructions (Author) and the other will be the one who executes the instructions and draws the figure (Actor). The author has to abstract the relevant information from the template and give instructions to his partner to draw the same figure from the drawing without seeing it. You must give instructions in an orderly manner, that is, create the algorithm. When you have finished giving all the instructions, evaluate if your partner has made the same drawing as the template. Roles will be changed so that both students experience the role of actor and author. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	What similarities and differences are there between the role of actor and that of author? Which is more complex and why?

INSTRUMENTED ACTIVITIES

Activity	**A game of sequences**
Action	Instrumented
Object	Physical
Student's role	**Actor**
Concept	Sequences
Learning goals	-Identify the beginning, intermediate steps and end of a sequence. -Manipulate the robot's direction symbols. -Listen to the association between the instruction and the behaviour performed -Manage basic orientation functions (up-down, front-back, right-left)
Materials	-Chained letters* -Ground Robot (Bee-Bot or similar) - "Who is who?" size for floor robot* *(See the Annexes of the activity developed)
Duration	60 minutes
Description of the activity	The teacher will introduce the concept of sequence as a series of ordered steps (5 minutes). The teacher will present the mat to the students. Time will be left to talk about the animals represented in it. Afterwards, students will be able to manipulate the ground robot with the direction arrows (robot buttons). Give them some time to explore how the robot works. It should be clear that the robot stores the programmed sequences, so if you want to start again you have to delete the previous ones. Likewise, when the right and left arrows are pressed, it only turns 90º but does not move forward. Finally, depending on the students' literacy level, either the teacher reads the chained letters or the students themselves read it. If they still do not know how to read, the teacher will read the chained cards and the students will have to guess which animal it is from among those on the mat. When you have guessed it, they will move the floor robot from the animal on the card that the teacher had with the description, to the corresponding animal. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	How many steps did the sequence have from one animal to another? What does each floor robot symbol mean? Could you design another possible route? What does this activity have in common with the one previously carried out about the dance of the day or building a figure with Lego...?

Activity	**Sequences with BeeBot**
Action	Instrumented
Object	Physical
Student's role	Actor
Concept	Sequences
Learning goals	Build sequences of steps like maps, directions, or instructions Describe the effect of each step in a sequence.
Materials	Printed labyrinth/challenge, printed arrows, floor robot
Duration	25-30 minutes
Description of the activity	In the last activity, we learned that robots can only follow the sequences we create if we place them in a specific way. Today we will create a map for a robot. This robot will understand it if we help it using arrows. Children are presented with a mat (maze) and a set of arrows in four directions (forward, right, left and back). You can use the ones we suggest or if you wish, make your own with discreet 15x15cm steps. Children must solve the maze by creating a map for the robot using the arrows. For example, in map 1: The robot must start from where the bee is, go through each of the flowers on the map and reach the hive. We notice that the different rugs have more flowers to increase the level of complexity.
Metacognitive prompts	How many arrows do you need to complete the maze? What does each arrow do? Can you point to your map and tell me the sequence of arrows you used?

Activity	**Getting to know ScratchJr**
Action	Instrumented
Object	Virtual
Student's role	Author
Concept	Sequences
Learning goals	Students can construct sequences of steps as maps, directions or instructions Students understand the association between instructions and expected behaviour.
Materials	Individual computer or tablet, internet connection, block guide to Scratch Jr ScratchJr App. | ScratchJr online Scratch Jr Guide | Block guide
Duration	20-30 minutes
Description of the activity	During this activity, students will have the opportunity to explore ScratchJr with the aim of becoming familiar with the block programming environment. It allows children to play and create their own codes by observing the different types of blocks available and the actions associated with each of them. We suggest working with ScratchJr's block guide and interface guide to support exploration. Rely on the ScratchJr blocks guide to generate together with the class a list of blocks that we would like to test. At the end of the activity, we try to answer the following questions together:
Metacognitive prompts	What new blocks did we meet? Did you use any blocks that surprised you?

Activity	**First sequences in ScratchJr**
Action	Instrumented
Object	Virtual
Student's role	Author
Concept	Sequences
Learning goals	Students can construct sequences of steps as maps, directions or instructions Students understand the association between instructions and expected behaviour.
Materials	Individual computer or tablet, internet connection, block guide to Scratch Jr ScratchJr App. | ScratchJr online Scratch Jr Guide | Block guide
Duration	20-30 minutes
Description of the activity	Children are tasked with creating incremental sequences to reach a given destination on a virtual map. These activities have been implemented on several free platforms, such as the Scratch Jr. app or the BeeBot app, among several available options. The key is to keep the sequences simple so that children become familiar with the new interface and use of the tablets. For example, using the Scratch Jr application, we select a background and we propose to generate a program that allows the character to move within that background.  How can I get the character from the yellow table to the blue table? This challenge has different solutions! Invite students to try various paths. For example:

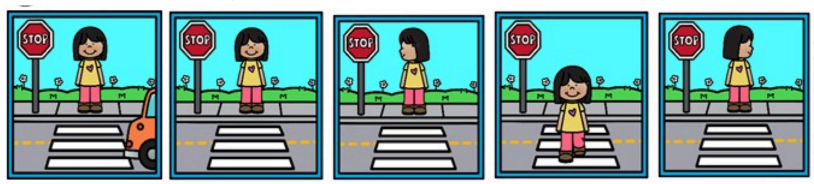
Metacognitive prompts

How did you give the character the orders?
Did the character do what you expected him to do?
How many steps did your sequence have?

Activity	**Programming movement**
Action	Instrumented
Object	Mental
Student's role	Actor (the student is the one who thinks up the instructions and programs them into the ground robot (Bee-Bot)).
Concept	Sequences
Learning goals	-Create sequences -Program the ground robot with the intended sequences -Understand the association between the instruction and the behaviour performed -Manage basic notions of orientation (up-down, front-behind, right-left)
Materials	-Ground Robot (Bee-Bot) - "Who is who?" size for floor robot* *(See Supplementary materials)
Duration	60 minutes
Description of the activity	The teacher will present the mat to the students. Time will be left to talk about the animals represented in it. One student must give a series of characteristics of an animal on the mat and the rest of the students must guess what animal it is. When they guess it, they must design the route/sequence of steps that they must program the ground robot so that it goes from one animal to the animal described by the student. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	How many steps did the sequence have from one animal to another? What does each floor robot symbol mean? Could you design another possible route? What does this activity have in common with the one previously carried out about the dance of the day or building a figure with Lego...?

Activity	**Programming movements II**
Action	Instrumented
Object	Mental
Student's role	Actor (the student acts as a robot, interprets and represents the instructions).
Concept	Sequences
Learning goals	-Identify the beginning, intermediate steps and end of a sequence -Manipulate address letters -Understand the association between the instruction and the behaviour performed -Manage basic notions of orientation (up-down, front-behind, right-left)
Materials	-Chained letters* -Robot costume* - "Who is who?" size for robot student* -Address letters* *(See the Annexes of the activity developed)
Duration	60 minutes
Description of the activity	The teacher will introduce the concept of sequence as a series of ordered steps (5 minutes). The teacher will present the mat to the students. Time will be left to talk about the animals represented in it. Afterwards, students dress up as robots and manipulate the address cards. The right and left arrows must be clear, it only implies a 90º turn but does not move forward. Finally, depending on the students' literacy level, either the teacher reads the chained letters or the students themselves read it. If they still do not know how to read, the teacher will read the chained cards and the students will have to guess which animal it is from among those on the mat. When they have guessed it, they will arrange the direction cards to get from the animal on the card that the teacher had with the description, to the corresponding animal. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts	How many steps did the sequence have from one animal to another? What does each symbol on the address cards mean? Could you design another possible route? What does this activity have in common with the one previously carried out about the dance of the day or building a figure with Lego...?

Supplementary activity

Activity	A day in pictures
Action	Enacted
Object	Mental
Student's role	Actor
Concept	Sequences
Learning goals	Identify the beginning and end of a sequence and the steps in between Understand a simple sequence of command model behaviour
Materials	Picture sequencing cards 
Duration	30 minutes
Description of the activity	Students will work in small groups (3-4 children). Each group will be presented with a set of 4-5 image sequences representing a routine or a spatial or temporal change. (For example, the process of getting dressed, watching a plant grow, brushing your teeth.) Students are tasked with arranging the images in the correct order to make sense of the images. Each group will then show the sequence to the class and explain what happens in each particular step.
Metacognitive prompts	Please explain your sequences to the class. How did you go about ordering your sequence? (If there are any errors) Is there anything you would like to change in this sequence? Was it easy to identify the first step?

EARLY YEARS COMPUTING

REPETITION

What are loops?

Using repetition can make our programming more efficient. We can see that the repetitions are based on a condition, for example: as long as X movement occurs, repeat this code 2 times.

Suggested trajectory

Preparation activities focused on the body (motor)			Suggested time
I.	with physical objects	Routines with Repetition	30 min.
		Repeating patterns	35 min.
II.	With mental objects	Routines with Repetition II	30 min.
Activities with symbols			**Suggested time**
III.	with physical objects	Repetition with BeeBot	60 min.
IV.	With virtual objects	First loops	30 min.
V.	With mental objects	Repetition with BeeBot II	30 min.

ENACTED ACTIVITIES

Activity	**Routines with repetition**
Action	Enacted
Objects	Physical
Student's role	**Actor** (the student is the one who represents the actions-instructions)
Programming content	Repetition
Learning objectives	-Identify repeated patterns within a sequence -Follow the sequence and enact the repetition -Understand the association between instruction and movement
Materials	None
Duration	30 minutes
Activity description	The teacher will introduce the concept of repetition/loop as a series of steps (sequence of instructions) that are executed repeatedly until the condition is no longer met (5 minutes). The teacher will give a series of instructions about a daily life activity (for example: brushing your teeth) so that the students can mimic the actions he or she dictates. It is important that the instructions provided are detailed so that the students are able to execute them correctly. For example: Let's imagine the routine requires washing our teeth. A possible sequence containing instructions could be: move the toothbrush from right to left, from top to bottom twice. Rinse with water three times, etc. Finally, teachers use metacognitive questions (5 minutes) to check for understanding of the task and concept.
Reflection/ Metacognition	What do you understand by repetition/loop? What was repeated within your sequence? Could you think of another possible thing we can repeat? Could you give an example of things you use repetition for in your daily life? What is the relation between condition and repetition?

Activity name	**Repeating patterns**
Type of actions	Enacted
Type of objects	Physical
Learning goals	Identify the beginning and end of a sequence and the steps in between Follow a set of instructions.
Materials	Rainbow colored beads and thread Or rainbow-colored stackable bricks
Duration	15-20 minutes
Task description	On this occasion, the creation of patterns using physical elements will be done emphasizing repetition. Encourage your students to generate repeated patterns. For example: green green red green green red Observe the created patterns together. How many times is it repeated? Encourage students to register the patterns using their notebooks or the whiteboard.
Reflection/Metacognition	How many times is the pattern repeated? How do we register it? Is there a way to simplify our sequence?

Activity	**Routines with repetition II**
Action	Enacted
Objects	Mental
Student role	**Author** (the student is the one who designs and dictates the instructions)
Programming content	Repetition
Learning objectives	-Plan repetitions/loops in a sequence of steps.
Materials	None
Duration	30 minutes
Activity description	In pairs or groups, students must give instructions/sequences to another group of students so that using their body they represent an everyday action (washing hands, frying an egg, getting dressed, etc.) which contains repetition. The students who dictate the actions will have to think about the steps that make up their daily activity with some repetition and give the correct instructions so that the rest of the group can execute the sequence of steps. Then the roles will be reversed so that both groups can experience the role of actor and author. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Reflection/ Metacognition	What is the repetition they have to perform? How have you explained the sequence and repetition so that your classmates understand and know how to interpret them? Have you been able to interpret the sequence and the repetition? How could you improve the sequence instructions? Can you come up with another possible repetition to add to the dance?

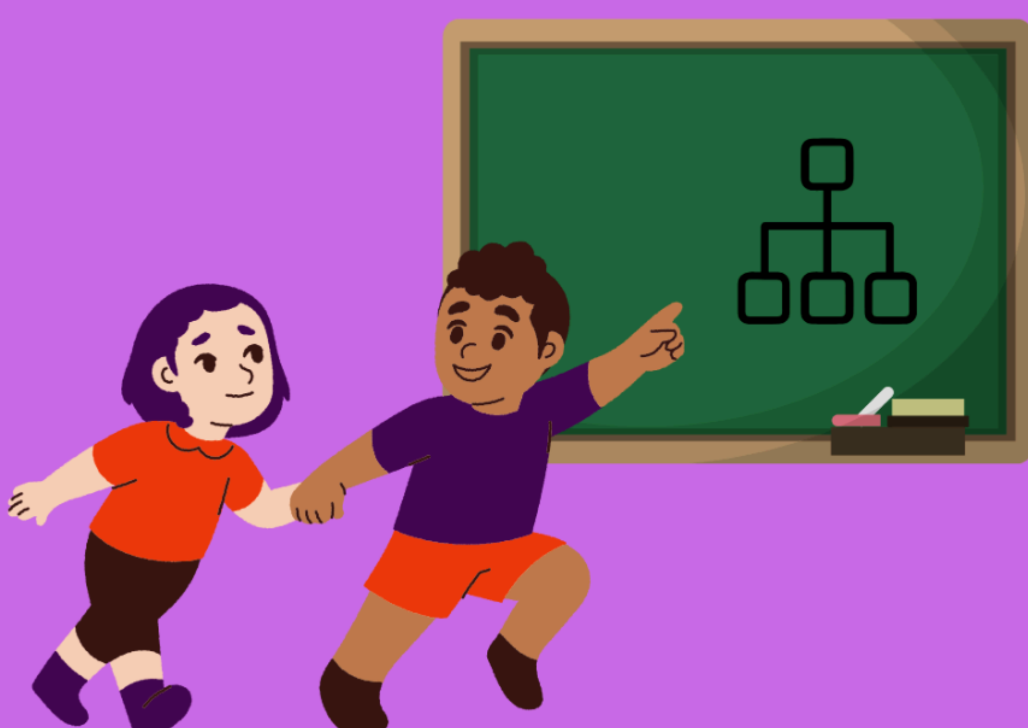
INSTRUMENTED ACTIVITIES

Activity	**Repetition with BeeBot**
Action	Instrumented
Objects	Physical
Student role	**Actor** (the student is the one who gives the instructions to the ground robot (Bee-Bot)).
Programming content	Repetition
Learning objectives	-Program a robot so that it executes a sequence containing repetition -Understand the association between the instruction and the behavior performed -Manage basic notions of orientation (up-down, front-behind, right-left)
Materials	-Cards*(see annex) -Ground Robot (Bee-Bot) - Mat*(see annex)
Duration	60 minutes
Activity description	The teacher will present the mat to the students and give them some time to discuss the animals represented on it. Afterwards, students will be able to manipulate the ground robot with the direction arrows (robot buttons). Give them some time to explore how the robot works. It should be clear that the robot stores the programmed sequences, so if you want to start again you have to delete the previous ones. Likewise, when the right and left arrows are pressed, it only turns 90º but does not move forward. Finally, depending on the students' literacy level, either the teacher reads the cards or the students themselves read it. The students will have to guess which animal it is and identify it in the mat. When they have guessed it, they will programme the robot to move to the correct animal. Possibilities to introduce conditions: the teacher will say, for example, go through X animal before reaching the final animal or if you touch X animal, then you have to go around yourself, etc. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check for understanding.
Reflection/ Metacognition	What condition have you programmed the robot with? Could you make up another condition? What do the conditions represented in the previous activities (free dance, bracelets, etc.) have in common?

Activity	**First loops**
Action	Instrumented
Objects	Virtual
Student role	**Author**
Programming content	Repetition
Learning objectives	Understanding repeat blocks Have a first experience with ScratchJr
Materials	ScratchJr
Duration	30 minutes
Activity description	In the sequencing activity, children created incremental sequences to reach a given destination on a virtual map. This time, we will use a similar task using ScratchJr (you can use the “activate grid” option to help children count the movements) but the challenge is to include the repetition block. Look at the image below: How can I get the character to move from the yellow table to the blue table using the repeat block?  
Reflection/ Metacognition	How many times did you have to repeat the movement? Can you find another solution without using it? How can using fewer blocks help us?

EARLY YEARS COMPUTING

SELECTION



Suggested trajectory

Enacted activities		Approx. time
I. Physical objects	Dancing with conditions	20 min.
	¿What 's next? Patterns with conditions	15 min.
	Orchestra conductor	20 min.
II. Mental objects	Dancing with conditions II	30 min.
Activities with symbols		**Suggested time**
III. Physical objects	Conditions I	60 min.
IV. Virtual objects	Events in ScratchJr	30 min.
V. Mental objects	Conditions II	30 min.

ENACTED ACTIVITIES

Activity	**Dancing with conditions**
Type of action	Enacted
Type of object	Physical
Student's role	**Actor**
Targeted concept	Condition
Learning objectives	-Follow the sequence and interpret the conditions -Understand the association between the instruction and the movement performed
Materials	None (Optional: music)
Duration	20 minutes
Activity description	The teacher will introduce the concept of condition as an element that allows you to choose between one option or another (5 minutes). Students are taught a dance that has some simple conditions. To create a sequence with a condition, we must first learn the steps of the sequence. The first sequence should start with just a few steps (3 or 4), for example: Both arms up, both arms down, step forward, step back and turn 360° from right to left. Afterwards, we introduce a simple condition to the challenge. For example: if the song plays, start dancing, and if the song turns off, stop dancing. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts and reflection strategies	What do we understand by condition? What condition have you interpreted with dance? Could you think of another possible condition in the dance? Could you give an example of a condition in everyday life? What is the difference between sequence and condition?

Activity	**¿What's next? Patterns with conditions**
Type of action	Enacted

Type of object	Physical
Student's role	**Actor**
Targeted concept	Identify the beginning and end of a sequence and the steps in between
Learning objectives	Follow a set of instructions.
Materials	Coloured stackable bricks
Duration	15-20 minutes
Activity description	Sometimes we can detect a sequence in nature. In this activity we seek to generate a sequence by introducing conditions. The group of students is tasked with generating patterns in the sequence again by combining colours but this time specific conditions must be met. For example: - If I put the colour blue, the colour red must always follow - If I put the colour green, the colour yellow or red cannot follow it The group is asked to reflect on the idea of condition and its relationship with the activity carried out.
Metacognitive prompts and reflection strategies	How many beads/bricks did your sequence have? What was the first step in your sequence? Can you explain to others the conditions we set for the sequence? Were the conditions met? Can you verify it in the patterns created by your classmates?

Activity	**Orchestra director**
Type of action	Enacted
Type of object	Physical
Student's role	**Actor**
Targeted concept	Conditions
Learning objectives	-Identify the beginning, intermediate steps and end of a sequence -Follow instructions -Understand the association between the instruction and the behaviour performed
Materials	None

Duration	20 minutes
Activity description	The teacher will introduce the concept of condition (5 minutes). The teacher acts as the orchestra director and the students will interpret the gestures and make the sounds. The teacher will give a series of signals using gestures indicating when and what sounds the students should make. For example, they can make animal sounds and depending on the gestures the conductor makes, they will be one animal or another. Example: Gesture with the fingers like a beak: bird sound (chirp chirp), hand gesture from one side to the other: cow (moo sound), etc. Possible conditions: if the teacher makes X gestures, students will sing louder, or if they make Y gestures, students will sing slower. Until you make Y gesture, continue making sounds. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts and reflection strategies	What is the difference between sequence and condition? What similarities and differences are there between the previous activities and these? What is the underlying programming content?

Activity	**Dancing with conditions II**
Type of action	Enacted
Type of object	Mental
Student's role	**Actor**
Targeted concept	Condition
Learning objectives	Understand conditions within a sequence
Materials	None (Optional: music)
Duration	30 minutes

Activity description	In pairs or groups, students must give instructions/sequences to another group of students, teaching them the steps of a dance which contains conditions. The students who lead the dance will have to think about the steps that make up their dance with some condition and give the correct instructions so that the rest of the group can execute the sequence of steps (the dance). Then the roles will be reversed so that both groups can experience the role of actor and author. Finally, ask the metacognitive questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts and reflection strategies	What are the dance steps? What is the condition they have to execute in the dance? How have you explained the steps and the condition of the dance so that the students understand it and know how to interpret them? Have you been able to interpret the steps and the conditions? How could you improve the step sequence instructions? Could you make up another possible condition to add to the dance?

INSTRUMENTED ACTIVITIES

Activity	**Conditions I**
Type of action	Instrumented
Type of object	Physical
Student's role	**Actor**
Targeted concept	Conditions
Learning objectives	-Identify the conditions of the instructions -Follow the sequence and interpret the conditions -Understand the association between the instruction and the behaviour performed -Manage basic notions of orientation (up-down, front-behind, right-left)
Materials	-Cards -Ground Robot (Bee-Bot) - Mat *(See annex)
Duration	60 minutes

Activity description	The teacher will present the mat to the students and provide some time to discuss the animals represented on it. Afterwards, students will be able to manipulate the ground robot with the direction arrows (buttons). Provide enough exploration time so that students are familiar with the robot. Finally, depending on the students' literacy level, either the teacher reads the cards or the students themselves read it. Students will have to guess which animal it is from the mat. When they have guessed it, they will move the floor robot from the animal on the card that the teacher had with the description, to the corresponding animal. Possibilities to introduce conditions: the teacher will say, for example, go through X animal before reaching the final animal or if you touch X animal, then you have to go around yourself, etc. Finally, ask the metacognition questions (5 minutes) to reflect on what has been learned and check the acquisition of the content.
Metacognitive prompts and reflection strategies	What condition have you programmed the robot? What did it consist of? Could you make up another condition? What do the conditions represented in the previous activities have in common?

Activity	**Events in ScratchJr**
Type of action	Instrumented
Type of object	Virtual
Student's role	**Actor/Author**
Targeted concept	Conditions
Learning objectives	Explore the use of event blocks in ScratchJr
Materials	Tablets or computer
Duration	30 minutes
Activity description	In this activity we propose to explore the use of blocks linked to events (for example "start on tap" or "start on bump"). Students are tasked with selecting a character and generating a program that uses the block "start on tap". We reflect together on how in order for the program to be executed, the tapping condition must be met previously. Next, we add another character with a program that starts to execute when the previous character bumps into it. Use the "start on bump" and reflect on the condition it implies.
Metacognitive prompts and reflection strategies	What blocks did you use to create the events? What condition has to be met for the program to run? Could you explain to someone else how you did it?

A.3 Phase 3:

A.3.1 Teacher interview protocol:

1. Please state your full name
2. What is your educational background?
3. What grade do you currently teach?
4. How long have you been teaching (overall)?
5. How long have you been teaching this grade?
6. Have you introduced or worked in any of the following thematic areas before? (Options include: Computer science Computer science concepts Tangible computing Computational thinking Physical computing Sequencing skills Order Conditional statements or selection Loops Any programming language or environment aimed at young children (such as Scratch Jr., Scratch, Makecode, MicroBit, Blockly, or other) Other programming languages (Java, C++, Python, R or others) Worked with programmable robots (such as BeeBot, Cubetto, KIBO, Qobo, Matatalab or others)
7. How interested would you say you are in computing science subjects? (Five-point Likert scale)
8. If I were to ask you to rank your self-confidence in teaching the following subjects, how would you rank them? (Options include: Reading/Writing/Language skills, Mathematics History, Computer science, Art)
9. What changes/adaptations do you think are most important when introducing computing science to young children? (4-7 year olds)
10. What teaching methods or strategies have you found effective in engaging students in computer science education? Have you ever implemented concreteness fading in your class?
11. If yes, in which areas? Could you provide an example?
12. How do you encourage students to reflect on their practices during class? Are there any specific practices you implement?
13. Please mark the concepts you think would be more accessible to young students. (Options include: sequences, conditionals, repetition (loops), modularity, abstraction, logic (AND/OR)).

14. What challenges do you envision for teaching computer science to young children?

15. Have you ever participated in professional development courses for computer science? If yes, which ones?

16. How would you rate your motivation for learning and participating in professional development courses about computer science? (Five point likert scale)

17. Are there any specific needs or resources you believe would improve computer science education in your area?

18. Is there anything you would change about the activities?

19. How were these activities different from what you had been doing before?

A.3.2 Post-session interview protocol for children

1. Could you please explain to me, using your own words, the activity you just did with your teacher and classmates? (Objective: exploring children's general understanding of the activity)

2. What would you say was the hardest part of the activity?

3. Can you select on this scale how hard you think the activity was?

4. Can you select on this scale how much you enjoyed this activity?

5. Exploration of the concept

In case the child brings up the concept explicitly during question 1:

5.a You just mentioned [sequence/repetition/selection] can you explain to me what that is to you?

OR

5.b Remember in the activity, the teacher highlighted the idea of [sequence/repetition/selection]. Can you explain to me what that is to you?

6. What connections do you see between the activity you just did and previous ones?

A.3.3 Intervention fidelity checklist

Section	Observation	Yes	Partially	No
Introduction	The class started with the introduction and presentation of the concept in general terms			
	The teacher used signalling strategies to highlight the importance of a new concept			
	The teacher used the concept word explicitly during this section			
Main Activity	The teacher implemented a practical exercise (could be enacted, instrumented or formal) activity that was aligned with the concept			
	Children were generally engaged and interested in the activity			
Wrap up	The teacher linked the practical activity to the concept introduced in the beginning of the session			
	The teacher highlighted the concept			
	The teacher implemented a strategy to check for understanding			
	The teacher used metacognitive prompts to promote children's reflection about the activity			
Lesson congruence	The teacher made an effort to connect the activity to previous activities			
	The teacher made an effort to connect the activity to children's previous knowledge			

A.3.4 Procedural rubric applied during activities

Domain	Fully achieved (2)	Partially achieved (1)	Not achieved/Needs improvement (0)	Not observed this session
Procedural	Child seems to comprehend and solve the activity timely	Child solves the activity with help or scaffolding	Child does not seem to comprehend or is unable to solve the activity	

A.3.5 Language test of temporal concepts (ECTE) sample item

:

Figure A.1: Sample item from ECTE task by Fitipalde (2021). Children are asked to organise the picture sequence and questioned on their notions of what happened before and after events.

Appendix B

Research ethics

University of Glasgow | College of Science & Engineering

Dr. Julie R. Williamson
Senior Lecturer

School of Computing Science
University of Glasgow
18 Lilybank Gardens
Glasgow G12 8QQ
Tel.: +44 141 330 3718
Julie.Williamson@glasgow.ac.uk

Glasgow, September 10, 2024

Ethical approval for:

Application Number: 300240002

Project Title: A grounded cognition approach to promote computer science conceptual understanding in young children

Lead Researcher: Dr Maria Kallia

This is to confirm that the College of Science and Engineering Ethics Committee has reviewed the above application and **approved** it. Please keep this letter for your records. Also please download and read the Collated Comments associated with your proposal. This document contains all the reviews of your application and can be found below the approval letter on the Research Ethics System. These reviews may contain useful suggestions and observations about your research protocol for improving it. Good luck with your research.

The Primary Investigator is responsible for ensuring all research records generated through from this research follows the requirements laid out by the Data Protection and Freedom of Information Office and the Export Control policy. The College of Science and Engineering Ethics Committee does not review these documents, but all ethical approvals are subject to compliance to Data Protection and Export Control requirements.

Sincerely,

Dr Julie R. Williamson

Dr Julie R. Williamson
Ethics Officer
College of Science and Engineering
University of Glasgow

Information Sheet For Participants [Parents]

Research Ethics committee reference number: 300240002

Research project title: A grounded cognition approach to promote computer science conceptual understanding in young children

You and your son/daughter are being invited to take part in a study about early learning of computing concepts.

It is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and ask us if there is anything that is not clear or if you would like more information.

Participation in this study is completely voluntary, you should only opt to participate if you want to and choosing not to take part will not disadvantage you in any way.

What is the purpose of this study?

This research aims to explore whether a set of activities designed to teach computing (specifically sequencing, selection and repetition) to young children have positive effects in their conceptual understanding of these abstract notions. In order to do this, we are inviting your child's class to take part in a set of educational activities with the aim of learning computing concepts. This set of activities is based on grounded cognition, a theory of learning which posits that engaging in action-based activities with concrete materials could scaffold children's learning. This study is conducted as part of the researcher's PhD thesis.

What will the study involve? How long will it take?

If you agree to take part, we will ask you to:

- Complete a brief questionnaire (completion time is approximately 20 minutes) which will ask about your child's development regarding executive functions (i.e the ability to control his or her behaviour)
- Consent to your child's participation in a set of educational activities to learn computing concepts. These activities have been co-designed between academic researchers and early years and primary school teachers. Activities will not differ significantly from activities which children might normally engage with everyday in their classroom. Children will take part in the activities with their classmates during regular school hours under the supervision of their teacher.
- Consent to your child taking part in a brief interview on their conceptual understanding of computing concepts after the intervention.

What are the possible risks of taking part in this study for me or my child?

There are no known risks or side effects associated with taking part in this study for any of the participants. If any participant were to have any discomfort during the study he or she may pause or withdraw at will.

Do we HAVE to take part?

Participation in this study is completely voluntary, and you are free to withdraw the participation of your child at any time. There are no consequences to withdrawing from the study and all data will be deleted upon notice.

What if my child does not wish to take part?

In addition to asking to sign an informed consent, we will also ask children if they wish to participate and to verbally express their agreement before each activity. If the child expresses he or she does not wish to participate in some or all of the activities they will be given an alternative task by their teacher and will not have to participate if they do not want to.

Will data be kept confidential?

All of the information will be stored anonymously and treated in accordance with the General Data Protection Regulation (2018). Participants will be assigned an anonymous code for all databases and any identifying information will not be included in any of this research's output.

What will happen with the results of this research study?

Anonymised findings will be available upon request after the completion of the analysis. We are not able to provide individual results of any of the gathered data or individual assessments. The results of this research will be published in a doctorate thesis and peer reviewed scientific journals or conferences. No identifying data will be included in scientific publication or other instances of scientific dissemination.

What should I do now? Who can I contact if I need more information or have questions regarding the study or my participation in it?

If you have any further questions please contact Miss Anaclara Gerosa a.gerosa-barboza.1@research.gla.ac.uk

This project is part of a PhD investigation and is supervised by Dr. Maria Kallia, maria.kallia@glasgow.ac.uk

You may keep this information sheet to keep and will be asked to sign a consent form to participate in the study.

Information Sheet For Participants [Teachers]

Research Ethics committee reference number: 300240002

Research project title: A grounded cognition approach to promote computer science conceptual understanding in young children

You are being invited to take part in a study about early learning of computing concepts. It is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and ask us if there is anything that is not clear or if you would like more information.

Participation in this study is completely voluntary, you should only participate if you want to and choosing not to take part will not disadvantage you in any way.

What is the purpose of this study?

This research aims to explore whether a set of activities designed to teach computing (specifically sequencing, selection and repetition) to young children have positive effects in their conceptual understanding. In order to do this, we are inviting you to take part in the co-design of the activities for children as your practical experience and expert opinion as a teacher is vital in creating developmentally appropriate educational practices. Besides testing the effects of an intervention, we seek to create learning trajectories for these skills in order to contribute to current educational practice. This study is conducted as part of the researcher's PhD thesis.

What will the study involve? How long will it take?

If you agree to take part, we will ask you to:

- Attend a focus group (approximately 45 minutes) where you will be introduced to a pedagogical framework and teaching materials and asked to provide feedback on them
- Try this pedagogical framework to teach three computing concepts in your class for 6 weeks

What are the possible risks of taking part in this study?

There are no known risks or side effects associated with taking part in this study. If any participant were to experience any discomfort they may pause or quit the study at will.

Do I HAVE to take part?

Participation in this study is completely voluntary, and you are free to withdraw at any time. There are no consequences to withdrawing from the study and all your data will be deleted upon notice.

Will my participation be kept confidential?

All your information will be stored anonymously and treated in accordance with the General Data Protection Regulation (2018). You will be assigned an anonymous code for all databases and any information which might identify you will not be included in any of this research´s output.

What will happen with the results of this research study?

Anonymised findings will be available upon request after the completion of the analysis. We are not able to provide individual results of any of the gathered data or individual assessments.

What should I do now? Who can I contact if I need more information or have questions regarding the study or my participation in it?

If you have any further questions please contact Miss Anaclara Gerosa a.gerosa-barboza.1@research.gla.ac.uk

This project is part of a PhD investigation and is supervised by Dr. Maria Kallia, maria.kallia@glasgow.ac.uk

You may keep this information sheet to keep and will be asked to sign a consent form to participate in the study.

CONSENT FORM FOR TEACHER PARTICIPANTS

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Research project title: A grounded cognition approach to promote computer science conceptual understanding in young children

Research Ethics Committee Ref: 300240002

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

- I understand that if I decide at any time before the research data collection that I no longer wish to participate in this project, I can notify the researchers involved and withdraw from it immediately without giving any reason. I understand that due to the nature of the study that it may not be possible to withdraw my data after taking part.
- I agree to have the interview recorded, so it can be transcribed.
- I consent to the processing of my personal information for the purposes explained to me. I consent for my participation to be recorded . I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.
- I understand that the outcomes of this study will be published as part of a study and may be published in conference processing or a peer reviewed journal, If I would like to receive a copy, I will email the lead investigator. I consent to my information being anonymously stored for use in future research.
- I am aware of the topics to be discussed in the procedure

Participant's Statement:

I ____ agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information provided by the researchers about the project and understand what the research study involves.

Signed Date

Investigator's Statement:

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· I understand that if I decide at any time before the research data collection that I no longer wish to participate in this project, I can notify the researchers involved and withdraw from it immediately without giving any reason.

· I consent to the processing of my child's information for the purposes explained to me. I consent for my participation to be recorded. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.

· I understand that the outcomes of this study will be published as part of a study and may be published in conference processing or a peer reviewed journal. If I would like to receive a copy, I will email the lead investigator. I consent to my information being anonymously stored for use in future research.

Participant's Statement:

I ____ agree that the research project named above has been explained to me to my satisfaction and I agree to allow my child to take part in the study. I have read both the notes written above and the Information provided by the researchers about the project and understand what the research study involves.

Signed   Date

Investigator's Statement:

I Anaclara Gerosa confirm that I have carefully explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the participant.

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