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Conceptual development in early-years computing education: a grounded cognition and action based conceptual framework

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ABSTRACT

Background and Context: Since the surge of grounded cognition (GC) theories in cognitive psychology, many studies have focused on demonstrating the importance of embodiment and sensorimotor activities on students' conceptual development. In computing education, however, there is not yet a conceptual framework for developing age-appropriate.

Objective: This paper brings these sets of work together, showing how the wider grounded cognition literature can be of value to computing education. The main objective of the paper is to suggest and set the theoretical foundations of a model for conceptual development in the early years of computing education.

Method: The paper is a conceptual paper and thus, it is based on an extensive account of relevant cognitive psychology and education literature.

Findings: The paper presents a model for conceptual development (EIFFEL -Enacted Instrumented Formal Framework for Early Learning in Computing). The general premise underlying the model is that programming concepts are first realised as actions performed on objects; as such, it aims to describe children's conceptual development in computing from their first actions on concrete objects to entirely abstract forms of action representation epitomised by a program.

Implications: The model constitutes the first attempt to theorise conceptual development in the early years of computing education; as such it is expected to be used for the design of learning trajectories that progressively advance children's conceptualisations from concrete, situated and multi-modal to formal and more abstract representations.

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Grounded cognition; computing education; unplugged computing; physical computing; computational thinking; conceptual development

1. Introduction

In recent years, there has been a movement towards emphasising the role of perception, the body, and the environment in shaping cognition. In contrast to the traditional cognitive science route, which considers the mind as an "abstract information processor", not connected to the outside world (Wilson, 2002, p. 625), the profoundly separate view –

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grounded cognition – argues that sensorimotor networks have a leading role in information processing and semantic retrieval (Hayes & Kraemer, 2017). The grounded cognition theories view the brain, the body and the environment as a continuous dynamic system; concept representations are multimodal and contextually dependent, and thus, they are recreated using the modalities[1] with which they were obtained (Hayes & Kraemer, 2017, p. 3). Thus, grounded cognition theories share the fundamental assumption that semantic information is represented and processed by the same neural systems that are involved during perception and action (Kousta et al., 2011).

Many research studies have highlighted the embodied nature of semantic knowledge and abstract thinking which constitute important considerations for investigating the influence of grounded cognition in learning and particularly on students' conceptual development. For example, embodiment theorisations have called for a reconsideration of the role of sensorimotor activities in learning and, as such, have influenced educational research in science, mathematics and linguistics (discussed in the next section); both pure bodily grounded experiences (no use of any digital tool) and interactive technologies (e.g. touch devices) have been employed to provide embodied experiences that enhance learning.

In computing education, sensorimotor activities can be mostly tracked in unplugged and physical computing learning settings which are widely regarded as valuable for introductory CS learning. CS Unplugged was originally created by Tim Bell, Mike Fellow and Ian Witten as an outreach program for primary school students; the program aimed to engage students with computer science and support them in understanding what computer science involves apart from programming (Bell & Vahrenhold, 2018). CS Unplugged culminated in 1999 with the online book "Computer Science Unplugged: Off-line activities and games for all ages". Since then, educators and researchers worldwide have adopted the unplugged computing approach as a pedagogy to make learning CS accessible to a more diverse student audience.

In the most recent literature review on unplugged computing by Huang & Looi (2019), the authors argue that even though the characteristics of unplugged activities are quite easy to comprehend (e.g. "no computers, sensory-rich, easy implementation, active participants, social interaction, games, stories, puzzles, and magic tricks"), there are still some critical issues that remain unanswered. Although the authors emphasise that a clearer understanding of the underpinning learning theory or pedagogical philosophy that guides the development and the design of these activities is needed, the critical question is how these activities can be part of a framework that emphasises the development of conceptual understanding in computing. Similar issues can be observed with physical computing – a range of tangible, embedded programmable devices that interact with the physical environment, e.g. Arduino, micro: bit. A literature review conducted by Waite (2017) emphasised that although teachers use physical computing activities in their computing classroom, there is limited empirical research that examines the effectiveness of this approach to learners' progress as well as the underpinning pedagogy. Similarly, Kalelioglu and Sentance (2019) highlighted the need for empirical studies that investigate the effect of physical computing on learning concepts and processes. Nonetheless, drawing mostly on Papert's constructionism as a theory of learning, this line of educational research focuses on enhancing students' learning experiences by constructing, building and interacting with tangible devices as a means to manipulate digital information. The integration of the physical environment and its objects and the learners' multi-sensory experiences and stimuli with computer interfaces can be seen as a way of humanising interaction between computers and individuals; physical computing brings together into one entity the environment in which one acts and perceives information and the digital world.

Both unplugged and physical computing activities are much discussed in relation to practising computational thinking (e.g. Brackmann et al., 2017). The term computational thinking (CT) was introduced by Wing to signify the discipline's ways of thinking. Since then, a vast majority of studies have focused on the way that computational thinking can be practised, whether with unplugged, plugged or physical computing activities. Several frameworks have been suggested that attempt to clarify what computational thinking entails (e.g. CSTA, I, 2011; Selby & Woollard, 2013). However, computational thinking is first and foremost a mode of thinking and as such, orthogonal to the debate of a common definition or ways of practising, it entails a rich theoretical and grounded investigation of its underlying foundations which, as in every mode of thinking (e.g. mathematical thinking), are the conceptual development and representations that must be considered to support students' learning trajectories.

Nonetheless, to date, there is no developmental conceptual framework or model that explains how conceptual understanding is developed in the early years of computing education (pre-primary and early primary education, 4–8 years old). This is particularly important for developing age-appropriate learning trajectories, facilitating students' conceptual difficulties in the discipline and building their self-efficacy (e.g. Kallia and Sentance, 2019; Sorva, 2018; Kallia & Sentance, 2021; Bayman and Mayer, 1983; Qian & Lehman, 2017). To design learning trajectories, Clements and Sarama (2012) consider three components: a. a goal b. a developmental progression and c. instructional activities. The developmental progression part is a significant part usually identified through theoretical and empirical models of students' development (ibid); these are learning models that describe the processes involved in students' realisations of a subject's topic or idea and include distinct levels of increasing sophistication and complexity. In computing education, these developmental progressions have not yet been hypothesised or studied.

To address this gap, we draw from research in the broad area of Grounded Cognition; research in this area has demonstrated that learning experiences stemming from manipulatives (tangible objects) contribute to the development of sensorimotor schemata that are the basis for abstract thought (Horn and Berns, 2019). As such, these findings and the theory that supports them are particularly important in computing education and are in alignment with the use of unplugged and physical computing activities in the early years of computing education.

Thus, the paper brings these sets of work together, showing how the wider grounded cognition literature can be of value to CS, particularly as countries around the world embark on mandatory school CS education from the early years. To this end, through a narrative overview of the grounded cognition literature and its application in education settings, particularly through the use of manipulatives, and relevant literature in computing education, we synthesise a framework that serves as a theoretical model of conceptual development in early computing education. The main aim of this paper is to develop this conceptual model and provide its underlying theoretical foundations. Such a model could inform the design and development of a sequence of computing lessons for early computing education (4–8 years old) that facilitates children's learning and conceptual development. The main research question of our study is the following:

How can Grounded Cognition theorisations form the basis of a theoretical, conceptual model that supports students' conceptual development and learning in early computing education?

The theoretical model for conceptual development in the early computing education (EIFFEL – **E**nacted **I**nstrumented **F**ormal **F**ramework for **E**arly **L**earning in Computing) is based on the premise that programming and computational thinking concepts are first realised as actions performed on objects; as such, it aims to contribute to children's conceptual development by scaffolding their actions from concrete to more symbolic forms of action representation. The model includes two dimensions of fading: vertical, highlighting the fading effect of manipulatives, and horizontal, highlighting the action fading effect as students move from one phase to the next. The model constitutes the first attempt to theorise conceptual development in early computing education and demonstrates how children's conceptualisations are gradually built from concrete, situated and multi-modal to formal or symbolic representations.

2. Methodological considerations for conceptual papers

It is important to highlight that the current paper is not empirical, rather it serves as a theoretical, conceptual body of work. As such, it is the authors' aim to suggest a conceptual model that introduces new ideas that can initiate further research in this area of conceptual development in computing education. In view of this, the authors' claims do not rely on experiments or other kinds of new data; but the authors' arguments stem entirely from theoretical and empirical research available in scholarly literature.

In this paper, we aim to develop a conceptual framework, and the ultimate goal of such frameworks is to be used as blueprints for framing further studies. McGregor (2020, p. 6) explains that "the aim of a conceptual paper is to advance and systematize knowledge. They do not include empirical data; rather they reflect theoretical thoughts and speculations about a topic where researchers make a specific argument by raising a point and then expanding on that thought through opinion or debate. The researchers provide supporting thoughts to substantiate their conceptual contributions.

Yadav (2010), in his paper on the decline of conceptual articles and implications for knowledge development, presents a framework for realising the significance of conceptual articles in knowledge development in social sciences and marketing. He argues that conceptual articles focus primarily on theoretical development, and as such, they do not present data or analysis for testing the theory. Mcneal (2011), in his chapter article about writing theory, conceptual and position articles for publication purposes, writes that theoretical, conceptual and opinion papers help challenge existing knowledge and lead to new understandings. He also argues that conceptual articles are the first step in theoretical development; a conceptual article, although quite similar to a theoretical article, is more abstract and not yet proven, whereas a theoretical article needs to have been tested.

Conceptual papers are usually discursive, which suggests that they involve reasoning and argumentation (McGregor, 2019). As such, the authors need to have a well-informed understanding of the issue and familiarity with a broad base literature which will form the grounding for the authors' new ideas and arguments. Although these papers do not have a rigid format, literature and how it is used is different from other papers (Mcneal, 2011). In conceptual framework papers, literature is used to "a. synthesise and integrate formerly disparate bodies of literature into a new conceptualisation of a phenomenon and b. employ integrative thinking to create provocative new conceptual perspectives by generating big ideas pulled together into a new conceptual whole" (McGregor, 2019, p. 10).

McGregor (2019) offers specific guidelines for writing a conceptual paper which are summarised below and adopted to build and present this paper.

- The *Introduction* should clearly include the authors position in a purposeful statement (e.g., the purpose of this paper is to present a conceptual developmental framework) which was already presented in the above section.
- The *Literature review* needs to persuade the readers about the merit of the conceptualisation based on the literature presented. As such, the authors need to provide a detailed review of the literature (section 3) and either integrate it with the new framework or present the new framework separately (section 4).
- To present the *New Conceptualisation*, the authors need to formally and precisely define all the concepts and underlying ideas and therefore demonstrate how these serve as building blocks of the new framework by taking support from the literature in combination with their logic to interweave the concepts into a new whole (section 4).
- The *Discussion* of a conceptual paper helps explain how the conceptualisation explains the phenomenon and affects practice as well as future research. Thus, the discussion serves as an opportunity for further research as well as discussing theory implications and practice implications (section 5).
- The *Conclusion* is a summary of the conceptual framework and a re-iteration of the conceptual points and arguments (section 6).

Following these guidelines, the current paper is not based on empirical data; rather its argument and the conceptual developmental framework stem from an extensive literature account of Grounded Cognition research, its implementation in education, particularly with the use of manipulatives, and computing education literature; thus, it does not suggest a theory of conceptual development and as such, it does not provide evidence (testing, and empirical evaluation) required when presenting a theory, as McNeal highlighted above; the conceptualisation presented in this paper will serve as the foundation to initiate new research experiments that will eventually lead to the formulation of a theory.

The structure of this paper is as follows: section 3 serves as a broad literature review that forms the groundings for our conceptual developmental model, while section 4 presents the model itself in detail by making connections to the literature presented in section 3. The paper ends with a discussion and future research directions.

3. Theoretical considerations in grounded cognition

The perspectives on the importance of the body and the environment in cognition vary substantially and range between two extremes: radical anti-representational views to representational-computational accounts. Theorists like Fodor (1983) and Kosslyn (1996) set the groundings of the computer metaphor of the mind which highlights the view that cognition emerges from computations executed on abstract, amodal symbols. This long-established view of representations being abstracted from modality experiences (amodal representation view) supports that conceptual knowledge is of symbolic format and is separated from modality-specific systems for perception, action and emotion (Barsalou et al., 2003). This means that the sensory information through which knowledge is acquired is not relevant to the representation of knowledge. On the other side of the extreme lies radical anti-representational accounts of cognition, usually known as radical embodiment or enactivism. Theorists like Gibson, Varela, and Di Paolo (e.g. Gibson, 2014; Di Paolo, 2018; Di Paolo et al., 2017; Varela et al., 1991) suggest different approaches whose explanatory power do not depend on the cognitive activity being dependent on computational or other representations; in a sense, what is radical in these approaches is the rejection of representations and computations – their accounts reject an appeal to mental representations (Heft, 2020). As Fuchs puts it, these approaches see the body as “the very locus of the subject, the source, and the medium of its relation to the world” (Fuchs, 2020, p. 11).. Di Paolo et al. (2010), for instance, underlined the ideas that constitute the basic enactive approach that challenges traditional views. These are autonomy, sense making, emergence, embodiment and experience, highlighting how organisms participate in generating meaning through their bodies and action; individuals, thus, do not passively receive information and translate it into internal representations but actively participate in the generation of meaning.

Between these two extremes – cognitivism and radical embodied accounts – are theorists like Barsalou et al. (2007) and Shapiro (2011) whose theories add a role of the body, the environment and the modalities into representational accounts of cognition (modal representations). The introduction of grounded cognition theories in cognitive sciences has emphasised the way that sensorimotor systems contribute to structuring conceptual representations of knowledge; within these theories, conceptual representations are of sensorimotor nature. Thus, these views, known as the modal representation view, in comparison to the amodal representation view, argue that conceptual knowledge is grounded in modality-specific systems and can be re-enacted by using the same systems without the stimuli being present (Shipp et al., 2018).

These theories recognise the importance of sensorimotor experiences to knowledge construction and, particularly, to the representation of both concrete and abstract concepts which is the central issue of the following subsection (3.1). As such, grounded cognition theories have influenced education practices by highlighting the important role of creating sensorimotor experiences during learning (discussed in subsection 3.2).

3.1. Conceptual representation and grounded cognition

In cognitive sciences, it is a common argument that concrete concepts have a cognitive advantage over abstract concepts (concepts that lack a visible referent) mainly because abstract words describe entities that are not physically or spatially restrained (Barsalou & Wiemer-Hastings, 2005); that is, abstract concepts lack concrete situations that can be realised. Situation availability or context availability refers to whether a situation exists in which a particular concept can be realised or occurred.

Schwanenflugel et al. (1988), in a series of studies, demonstrated the role of situation availability across different cognitive tasks. The authors argued that concrete concepts can be accessed, understood, and recalled much faster than abstract concepts due to the contexts available for their realisation. To demonstrate that these differences are indeed stemming from the concept's situation availability, the researchers performed a number of several experiments manipulating the situation availability condition for concrete and abstract concepts. When the researchers provided contexts for the abstract concepts too, the processing and accessing speed of concrete and abstract words were similar. This suggests that situation availability has a critical role in accessing and understanding concrete and abstract words, and thus, the meaning of words is not formed in isolation, e.g. as a set of features, but rather the meaning stems from background situations.

Barsalou and Wiemer-Hastings (2005) further proposed that concrete and abstract words differ in their focus within background situations. Specifically, while concrete concepts focus on objects, abstract concepts focus on social, events and introspective content, and these explain the reason why abstract concept representation is regarded as more complex. In their experiment, they asked participants to describe the situations in which a particular concept appeared. Although the participants produced similar distributions of information regarding agents, objects, settings, events and mental states both for the concrete and abstract concepts, differences occurred related to the content and complexity of the information. Specifically, abstract concepts focused more on mental states and events, whereas concrete concepts referred mostly to objects and settings. Additionally, abstract concepts contained more information and deeper structures. Regardless of these differences, both abstract and concrete concepts included situational information.

According to Barsalou (2008), the conceptual system shares mechanisms with modality-specific systems which implies that it does not work independently to represent concepts as it is supposed by amodal theories.Barsalou's (2008) position of grounding concepts claims that concepts are represented through reactivation of the same, modality-specific, neural patterns evoked by the encoding experience (Shipp et al., 2018). This suggests that the conceptual system stores information attached to a situation such as the surroundings, objects, people, and introspective conditions like affect, which are then simulated for concept representation in the absence of stimuli. Barsalou (2009) gives the following example: when processing a dog, the visual system concentrates on colours, movement, configural properties, surfaces, while other modal systems focus on the dog's sound (auditory system), how it feels to touch a dog (haptic system), and the actions performed by and on a dog (motor system and proprioceptive system[2]). Other modal systems engage with emotions (introspective), e.g. the emotional reaction with interacting with a dog. These features become active in the corresponding modal systems and, on later occasions, they can be re-enacted for representational purposes. For instance, to remember an experience with a dog, neurons partially reactivate the visual, motor and other modality states that were active when a dog was perceived. Simulations and simulators are the central mechanisms in this process; simulators gather together multimodal information across specific instances of a category (e.g. DOGS), while simulations represent specific conceptualisations of the category. For instance, a DOG simulator, depending on the situation, might simulate a sleeping dog or a sheepdog (simulation).

Other grounded cognition approaches focus on the role of language for grounding abstract concepts and align more with weaker versions of embodiment. For example, from the cognitive linguistic perspective, abstract concepts are grounded with the use of conceptual primitives (image schemas) and conceptual metaphors (e.g. an argument is war, time is money, Lakoff & Johnson, 1980). Although there is evidence that supports the role of metaphors in conceptualising abstract concepts, concerns refer mostly to whether their role is fundamental in the development of these concepts or they mostly offer structure to previous conceptualisations (Kousta et al., 2011). Other approaches also highlight the role of the linguistic system and affect in the grounding of abstract concepts. For instance, Vigliocco et al. (2009) argued that two types of information account for the representation of both concrete and abstract concepts, namely, experiential (sensory, motor, and affective) and linguistic. The difference between concrete and abstract concepts lies in the prevalence of sensorimotor information as groundings for concrete words and the prevalence of affective and linguistic information as the groundings of abstract concept meanings.

The role of the linguistic system is also considered in Barsalou et al. (2008) theory of language and situated simulation of knowledge (LASS theory). The theory posits that the simulation system (referred to in the previous paragraph) is incorporated with the linguistic system and these interactions between the linguistic and simulation system are what gives humans strong conceptual processing skills (Barsalou et al., 2008). In particular, the theory suggests that when a word is perceived, the linguistic system is engaged first (and may engage closely related words) which assists in activating associated simulations. In particular, information in perceptual, motor, and introspective brain areas is activated to represent the concept in a possible situation, and thus, prepare individuals for situated action.[3] One fundamental premise in this theory is that simulations reflect deep conceptual information, whereas linguistic ones are more superficial. However, in specific tasks, the linguistic system can be enough for performing a task, whereas when it is inadequate, the simulation system must also be engaged. Interestingly, during reasoning and problem-solving, both systems are active: individuals are engaged both in simulating the current situation, which represents the content of thought, and in verbalising about that which represents the tools for indexing, handling and directing this content. Translating that to educational settings, the authors suggest that students' understandings of a domain engage both the linguistic and simulation systems. Some students will only be able to reiterate memorised verbal descriptions, but others will be able to handle and direct simulation of the domain demonstrating deep understandings of it.

Independently of the way that these approaches have endeavoured to explain cognition, they do all reject the view of knowledge representation in semantic memory through amodal symbols and even if the brain includes amodal symbols, these collaborate with modal representations to create cognition (Barsalou, 2008). Thus, as we said in the beginning of this section, we could argue that Grounded Cognition (as was presented in this section and based on Barsalou's accounts) positions itself somewhere between the two extremes: anti- representationalism and representationalism; it recognises the significance of the brain, body and the environment in shaping cognition but still assumes representation power to the brain. Grounded cognition rejects symbolic representations of amodal form. Matheson and Barsalou (2018, p. 15) accurately describe this as follows:

> representations are neither full-fledged reproductions of objects, places, or people in the environment, nor are they amodal or implementable in just any physical system. Instead, representations are highly constrained by the physical system they find themselves in . . . One major goal of grounded research is to determine what features (e.g. primary sensory and motor) and conjunctions (e.g. multimodal) are represented in the brain's 'maps' and how their activation is constrained by the situatedness of the organism.

Grounded Cognition theory has direct implications in educational settings regarding the way cognition emerges from the body's interactions with the environment and how perception and action are related to conceptual development(Shipp et al., 2018). Instead of focusing on the dichotomy of brain and body, Grounded Cognition theory calls for a view that perceives the mind as a greater system in alignment with the body and the environment and the interactions that stem from it (Campbell, 2017).

3.2. Grounded cognition in education settings

The importance of sensorimotor activity in educational settings is rooted in the work of many psychologists like Piaget and Bruner, as well as known educators like Maria Montessori, to mention just a few. Bruner's view of learning as a process of active discovery and his interest in the representation of knowledge led him to propose three stages of representation: enactive, iconic and symbolic. In the first one, children's development is based on their interaction with the environment and manipulation of objects (Smidt, 2013); it is a kinaesthetic learning experience and concerns organising action, being able to employ several means to achieve a goal in an ever-changing environment (Bakhurst & Shanker, 2001). In the iconic stage, the children generate mental images of objects and experiences so that these can be used without the actual referent for furthering their understandings (Smidt, 2013). It is mostly a stage of active perceptual learning that guides understanding and action (Bakhurst & Shanker, 2001). The final stage refers basically to abstract thinking through the development of language and symbolic systems that reorganise previous experience. For Bruner, these three stages were seen as three ways in which humans represent the world or reality. In a similar vein, Maria Montessori's work also supported the important role of the environment and particularly object manipulation in supporting children's neuropsychological development; this led Montessori to argue that the hands are the instruments of man's intelligence (Montessori, 1959). In fact, many studies in educational settings have highlighted the role of manipulating objects or manipulatives, whole-body movement, hand movement and gesturing[4] as important in cognitive development.

In the following section, we will pay particular importance to the literature regarding the use of manipulatives in education settings. This is mainly due to two reasons: first, as it was highlighted in the above paragraph, the role of manipulatives in children's early cognitive development is critical, and second, because early computing education activities, such as unplugged activities as well as physical computing activities, are themselves means of manipulating physical or virtual objects, whether with direct physical action (e.g. unplugged settings) or through more sophisticated or advanced types of actions (discussed in section 4). To this end, the theoretical considerations regarding the use of manipulatives in education settings for conceptual development as well as issues that need to be taken into consideration when manipulatives are used as a means of scaffolding of children's concept acquisition need to be particularly explored.

3.2.1. Manipulative

In line with the above theorists, many studies, particularly in mathematics education, have explored how interacting with concrete objects facilitates learning. Manipulatives are objects (digital or not) that children interact with to learn; they are supposed to assist students with concretising their knowledge by communicating concepts, ideas and working on problem-solving tasks (Belenky & Nokes, 2009). In this sense, manipulatives can support the development of abstract thinking especially for younger children who have the innate tendency to explore the environment by physically interacting with objects (Tran et al., 2017). N. McNeil and Jarvin (2007) identified three reasons regarding the way that manipulatives support learning: the first is that manipulatives provide an additional way to communicate information, the second is that manipulatives trigger real-world knowledge, and the third refers to memory and the way it is improved through physical activity. The latter refers to the relationship between a symbolic concept and the perceptual information and action with the manipulatives (how interaction with the manipulative relates to symbolic concepts). For instance, research on extended cognition also suggests that the use of external representations (e.g. manipulatives) decreases the extent of cognitive effort; Manches and O'malley (2012) highlight this as the manipulatives' cognitive offloading mechanism for supporting learning. In the same vein, embedded cognition claims that the perceptual and interactive richness of working with manipulatives can decrease the students' cognitive load by embedding the students' cognitive activities in the environment (Pouw et al., 2014) . Another way that manipulatives support learning is through the use of conceptual metaphors and analogical reasoning. By organizing materials as metaphors of more abstract concepts, children may develop more abstract ideas by using metaphorical projections of schemata constructed through sensorimotor experiences in the physical world (Manches & O'malley, 2012).

3.2.1.1. Issues with working with manipulatives. Carbonneau et al. (2013) conducted a systematic literature review on the use of manipulatives in mathematics. Their analysis showed that instruction through manipulatives produces significantly better results in comparison with abstract symbolic instruction, particularly on retention and less on problem-solving, transfer, and justification. However, just manipulating objects in an arbitrarily way is likely not to bring about the intended learning effects; manipulatives do provide support and scaffolding, but they do not directly transfer the taught concept to the learner (Sarama & Clements, 2016) and they do not secure meaningful learning especially if they are employed only as a fun learning activity or generally when they are not used properly (Moyer, 2001 as cited in Kamina & Iyer, 2009). In a study conducted by

Belenky and Nokes (2009), three conditions were examined in terms of manipulatives' effect on students' learning and knowledge transfer. The learning condition which included concrete manipulatives with metacognitive prompts (reflecting questions on various aspects of the learning and problem-solving process) demonstrated better transfer of a procedural skill than those trained with abstract manipulatives or concrete but with problem-focused prompts (questions directly linked to current goals and tasks) instead of metacognitive. The authors suggest that concrete manipulatives accompanied by metacognitive prompts help students ground new knowledge in prior knowledge and assist them to abstract through reflection.

Concerns regarding the use of concrete manipulatives and knowledge transfer have been raised by other researchers too (e.g. Goldstone & Sakamoto, 2003; Son & Goldstone, 2009; Tran et al., 2017). The most common argument is that by using highly realistic situations and materials, knowledge may be connected to this particular situation which makes transfer to other situations difficult (Belenky & Nokes, 2009); the concreteness and perceptual richness of physical manipulatives may constitute an issue on transferring knowledge and generalising it to different contexts (Tran et al., 2017). Interestingly, Tran et al. (2017) maintain the view that in order to make the connection between concrete and abstract objects or concepts, digital manipulatives may afford more opportunities. They suggest that concrete manipulatives are better for learning instruction at the beginning, but digital manipulatives are better for transferability; a scaffolding technique that moves students from concrete manipulations to digital could afford the benefits of both representations. This observation is supported by other researchers too. For instance, Soury-Lavergne (2016) examined the dual nature of artefacts (concrete and digital) and their added value to learning and presented the importance of connecting the concrete and virtual manipulatives to combine the advantages of both and overcome their limits. To this end, Fyfe et al. (2014) suggest concreteness fading as a process to connect the concrete to symbolic/abstract knowledge through three stages: first, engagement with concrete manipulatives, second, engagement with analogical representations that fade away the concrete properties of the physical manipulatives, and finally, presenting students with abstract and symbolic representations. In their study, N. M. McNeil and Fyfe (2012) examined the effectiveness of three conditions (concrete, abstract/symbolic, and concreteness fading) to undergraduates' learning of modular arithmetic. Students in the concreteness fading condition demonstrated the best transfer performance even three weeks after the intervention.

3.2.1.2. Concreteness fading when working with manipulatives. Concreteness fading (Fyfe et al., 2014) targets the problem of transfer; it is a theory of instruction that enhances students' ability to transfer knowledge from working with concrete manipulatives or concrete situations or processes to abstract ideas and unknown problems. The theory suggests the use of three steps (based on Bruner's three stages of representation) to achieve this transition: starting from enacting a concrete instantiation of a concept, moving to an iconic interaction and then fading to a more abstract representation. Therefore, concreteness fading could be regarded as a theory of instruction intended to facilitate the links between multiple representations along a progression. Goldstone and Son (2005, p. 70) define concreteness fading as "the process of successively decreasing the concreteness of a simulation with the intent of eventually attaining a relatively idealised and decontextualised representation that is still clearly connected to the physical situation that it models". Therefore, the theory aims to facilitate learning by engaging with a *physical instantiation* of the concept, by *decontextualising* the initial representation so that to promote transfer, and by *highlighting the relationship between representations* as reciprocal referents of the same concept.

Fyfe and Nathan (2019) suggested six hypotheses about the progression of concreteness fading that should guide research and practical instructional design. These principles highlight mostly that the process of fading progression should be smooth; for instance, instead of two direct phases (concrete to abstract), three phases should be designed; the order of the progression should move from a concrete to a more abstract representation rather than the opposite; the first phase should include a physical manipulative, presenting the three stages in a sequence would be more effective than presenting them at the same time and each phase should reference the previous one. The latter argument, which refers to presenting the three representations in a sequence rather than using them at the same time to depict differences, is extremely important; it highlights that the different representations should be seen as mutual referents of the same concept rather than different ways of representing a concept.

3.2.1.3. Recommendations. By reviewing relevant literature, Laski et al. (2015, p. 2) has suggested the following principles for employing manipulatives to inform classroom practice: "a. use manipulatives consistently over a long period of time b. begin with highly transparent concrete representations and move to more abstract representations over time; c. avoid manipulatives that resemble everyday objects or have distracting irrelevant features; d. explicitly explain the relation between the manipulatives and the concept". The first principle highlights the need for students to be exposed to manipulatives for a long period of time because students do not easily interpret the meaning of objects or actions performed on objects. Martin (2009) suggested that using the same or similar objects to solve problems leads to deeper understandings and relations between the manipulative or the process and the abstract concept (as cited in Laski et al., 2015). The second principle highlights the importance of using closely related manipulatives (or bodily motion or action) with the concept they represent to facilitate conceptual mapping; this is particularly important when students are first introduced to the corresponding concept. Eventually, students need to progress to the use of more abstract representations. This transition is known as concreteness fading, and it was discussed above. The third principle emphasises the fact that manipulatives resembling everyday objects or objects with many irrelevant features may actually impede learning; this is because children may be distracted and it is, thus, more difficult to make the connection between the concept and the actions with the manipulative. The final principle underlines the importance of instruction to make explicit connections between the concept and the manipulative as young students have difficulties abstracting meanings. This observation was also supported by Manches and O'malley (2012) who highlighted that manipulatives' symbolic significance is only accorded by the context of use and that support is needed for connecting manipulatives with the concept they represent: when students interact with objects, their focus turns on both manipulating objects and on understanding the connection of their actions with the concept they represent – this duality poses difficulties on students' learning and thus, it is problematic to assume that understanding the underlying concept while acting on manipulatives is evident to students.

3.2.1.4. Final observations. Overall, manipulating artefacts to enhance conceptual understanding entails a rich understanding of their mechanisms and how manipulatives and the sequence of learning activities should be designed to support students' conceptual development. Unplugged and physical computing activities can also be seen as a way of working with manipulatives: early computing education activities are themselves a means of manipulating physical or virtual objects, whether with direct physical action (e.g. unplugged settings) or through more sophisticated or advanced types of actions (discussed in section 4). Therefore, when we are considering conceptual development where these two sets of activities are included, it is important to consider all the issues and suggestions outlined above. This will be further explained in section 4.

3.3. Early computing education and grounded cognition

In computing education, computational thinking (CT) is regarded as the mode of thinking underlying our discipline's scientific way of thinking. In the early years of computing education, CT is mostly practised through unplugged activities, physical computing activities like introductory robotic systems, and block-based programming languages for early years (e.g. ScratchJr) which are considered fundamental to engage students and facilitate their understandings of CT concepts.

Unplugged activities, particularly, have been employed to introduce students to concepts central to CT and help them gradually organise their experiences. For instance, Bell and Lodi (2019) advocate that CS Unplugged activities provide scaffolding to a constructivist approach to subject content without computers with which students construct meanings of key CT concepts. The unplugged approach emphasises that computational thinking can be promoted without introducing the challenges of learning the syntax of a programming language. Apart from the plethora of unplugged activities which can be found online (e.g. https://csunplugged.org/en/), low-cost games have been developed, such as Robot Turtles, which introduce young children to CT by engaging them with sequences and problem solving (Sullivan & Bers, 2019). Introductory robotic systems (such as KIBO) are also employed with which students can interact and manipulate physically. These systems use tangible programming languages and are developmentally appropriate for early years children (e.g. Code-a-Pillar created by Fisher-Price for preschool-aged children, the Bee-Bot robot, and the KIBO robotics kit). More advanced physical computing devices that require programmable construction (e.g. Lego Mindstorms and Arduino) are used for students of more advanced age. Block-based programming languages, such as ScratchJr, are also used in early childhood computing education (5–7 years old) since they are developmentally appropriate (Flannery et al., 2013), while block-based tools like Scratch are used for children older than 7 years old.

The underlying theory of most of the above activities aligns with Papert's constructionist theorisations; he suggested that experiences that include the active construction of artefacts promote meanings and knowledge development (Kynigos, 2015), and Bruner's view of learning as a process of active discovery during which a child's actions and the environment in which she acts influence these actions and transform her into a problem solver (Ruiz and Linaza, 2015). Most importantly, the way that these activities are organised aligns with grounded cognition views which underline the relation between conceptual development and physical activity or manipulation: in unplugged computing settings, students engage whether with physical manipulatives (non-digital) or with activities that engage the whole body; in physical computing activities, research focuses on enhancing students' learning experiences by constructing, building, and interacting with tangible devices as a means to manipulate digital information and thus, it brings together into one entity the environment in which one acts and perceives information with the digital world.

Therefore, action is central in the development of early years computing conceptual understandings. In their article, "Where's the action? The pragmatic turn in cognitive science", Engel et al. (2013) advocate cognition as action and call for a transformation from a theory of cognition to a theory of action. As such, action is fundamental to students' conceptual development and in computing education, it is manifested when students interact with physical or virtual objects (manipulatives). For example, in unplugged computing activities and physical computing activities that do not require coding (e.g. introductory robotic systems), it is expected that through body movement and actions performed on physical objects, students would start constructing the meaning of the underlying computing concept that the activity refers to. The same is expected through physical computing activities that require coding, but this time students engage with code to manipulate and control objects; in this case, students' actions are in a more formal or symbolic form – action is expressed through coding. Thus, action is fundamental in early conceptual realisations in computing, and this view is in direct alignment with Grounded Cognition theories which highlight that cognition emerges from interactions with the environment and that perception and action are related to conceptual development (Shipp et al., 2018).

3.4. Summary

The surge of grounded cognition (GC) theories in cognitive psychology has emphasized the role of perception, action, and the sensorimotor system on students' conceptual development. These theories emphasise that cognition is not amodal and detached from the world; a central theme in these theories is that "cognition guides effective action in the world … and acts as a mediator between perception and action" (Barsalou, 2020, p. 3); perception, action, sensorimotor systems, the body, and the environment are all aspects that form cognitive representations. Thus, grounded cognition theories view the brain, the body and the environment as a continuous dynamic system; concept representations are multimodal and contextually dependent and thus, they are recreated using the modalities with which they were obtained (Hayes & Kraemer, 2017, p. 3). In other words, grounded cognition theories share the fundamental assumption that semantic information is represented and processed by the same neural systems that are involved during perception and action (Kousta et al., 2011). As such, grounded cognition perspectives conjecture that sensorimotor processes, action and perception are critical to learning since they are linked to cognition.

In computing education, the influences of the aforementioned theoretical considerations are evident in constructionism, a constructivist approach populated by Papert that underpins most of the theoretical organisation of computing activities. Specifically, grounded cognition accounts can be traced mostly in the use of unplugged and physical computing activities. However, to our knowledge, there is still a framework to be developed that brings together the practical and empirical work that has been done in computing education research and theoretical considerations of conceptual representation, development and understanding. To this end, our paper capitalises on action as the central process of early conceptual development, and by doing that, it draws from grounded cognition theorisations to suggest a theoretical model for conceptual development in the early years of computing education (EIFFEL – **E**nacted **I**nstrumented **F**ormal **F**ramework for **E**arly **L**earning in Computing). For our conceptual developmental framework, the considerations presented in the section about manipulatives are critical as we see both working with unplugged activities and physical computing activities as actions performed on objects to manipulate them or control them. Therefore, concreteness fading and the three phases with which it is implemented will be the foundations of our conceptual framework presented in the following section.

4. A theoretical model for conceptual development in early computing education

This section aims to present the theoretical model for conceptual development in early computing education and demonstrate how it is grounded in the literature presented above.

4.1. Action as central to development of computing concepts

As was highlighted in section 3.3, during early computing education, children engage in activities that require them to act on objects and manipulate them accordingly to achieve a goal. Cognition, therefore, emerges from children's interactions with the objects of the environment and thus, actions and cognition are interconnected; actions form the grounding for students' early conceptualisations in computing education. The underlying idea of our model, thus, is that computing concepts are first realised as actions, and as such, it is the actions that need to be abstracted to lead to more abstract and symbolic conceptualisations of computing concepts in early computing education. This view aligns with Boncoddo et al. (2010) who argued that since representations are grounded in action, then for new representations to emerge, actions have the major role. Within the enactive paradigm of grounded cognition theories specifically, Varela et al. (1991) advocated cognition as an embodied action.

As such, our model of conceptual development in the early computing education (EIFFEL) incorporates into its structure the notion of action as a fundamental computing concept for early years conceptual development and comprises three distinct phases as shown in Figure 1: Enacted, Instrumented, and Formal. The model comprises one central dimension:

- Horizontal - Action Concreteness Fading (ACF): which refers to trajectories across the three phases and is the central focus of the model

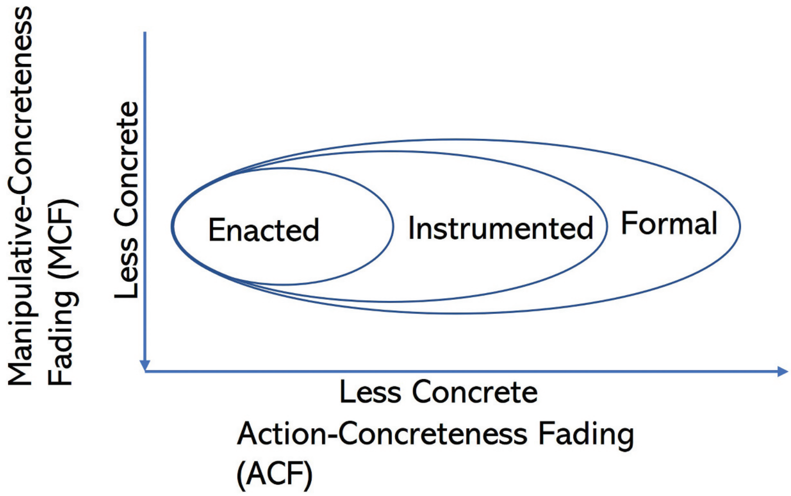

Figure 1. EIFFEL: phases of conceptual development in early computing education and dimensions.

Within each phase (Vertical dimension), fading can take place (not compulsory but recommended) in the way it was presented in section 3.2.1.2: that is the Manipulative Concreteness Fading (MCF) which focuses particularly on the type of objects children engage with and their concreteness. Following Reed's (2018) taxonomy which highlights three types of actions and objects (physical, virtual, mental), we also recognise the following types of objects in computing:

- physical objects embedded in the physical environment
- virtual objects are objects embedded in a digital environment, and
- mental objects refer to objects embedded in an individual's mental representations (e.g., mental image, mental model).

Action Concreteness Fading (ACF) considers actions as children's first conceptualisations; ACF shifts the focus from the manipulative per se to the type of action performed and thus, imposes a dual pedagogical challenge: the first refers to what type of actions children engage with and the second refers to how these actions can be scaffolded and sequenced so as to achieve more abstract conceptualisations; eventually, we want children to advance their conceptualisations from the concrete situations they engage during their interaction with the environment's objects/tools to more advanced conceptualisations.

4.1.1. EIFFEL and types of actions

The first issue that arises when actions are considered as fundamental to children's conceptual understanding is what type of actions children engage with. In computing education, there are different types of actions that can be performed as well as different types of objects upon which actions can be performed. We recognise four different types of actions:

- physical actions: these are actions like whole body movement or partial body interactions, hand movement and gesturing with high action congruency. These actions are mostly oriented towards manipulating objects (e.g., sorting cards, assembling, or putting together pieces of an object) but they can also include no manipulatives (e.g., a sorting dance, a movement on a mat).

• instrumented - symbolic actions: actions which include the use of hands or fingers to arrange/create/control symbolic instructions to control and manipulate an object.

• formal actions: actions which include the use of a formalised language to control and manipulate objects.

• mental actions: actions we perform mentally, with our minds (e.g., imagining, deciding, planning etc. we will not pay attention to these types of actions but readers can refer to Peacocke (2021) for more information)

Additionally, apart from the type of actions, we recognise one more dimension of actions: action congruency which highlights whether the action performed is semantically related (or integrated) to the learning aim. Skulmowski and Rey (2018) suggest that for describing an embodied learning setting, it is important to emphasise whether the form of embodiment is truly integrated into the learning task (high action congruency) or it is an incidental characteristic (low action congruency). The integrated form of embodied learning refers to "task-related embodiment manipulations" and examines exchanges between mental processes and the physical environment during task completion. The importance here is that there is a semantic relationship between the bodily activity and learning target, and thus, the bodily movements are content-related (e.g. bodily enacting the meaning of words). In comparison, the incidental forms of embodied learning refer to bodily priming effects, how the body primes cognitive processes when the body's actions are not semantically linked with the learning content; in other words, what the effects that some actions or cues have on the body influence cognitive processes (e.g. carrying weight when learning new words can be perceived as a cue of importance or difficulty but carrying weight is not semantically related to the importance or difficulty of a word, Skulmowski & Rey, 2017). A highly integrated form of embodiment demonstrates a semantic relationship between learning aims and contents and bodily activity. Thus, in our model, which considers conceptual development as stemming from the different actions students perform, high action congruency indicates a semantic relationship between the action performed and the learning target and should be a criterion for designing activities that are supposed to develop students' conceptual understandings.

The different types of actions are incorporated in each of the model's phases as it is illustrated in the following subsection.

4.1.2. EIFFEL and the action-concreteness fading process

The second issue mentioned above refers to the way actions can be scaffolded and structured in order to lead to a more advanced conceptual understanding. Action-concreteness fading highlights that action is in the centre of early conceptual development and thus, apart from the manipulative, actions need to be abstracted and fade away to advance children's conceptualisations.

Therefore, our model's *Enacted* phase is a concrete stage which is concerned with concrete manipulations and physical actions. In computing education settings, most unplugged activities (action congruency should be explicitly highlighted) are located in this phase, as does working with manipulatives that can physically be manipulated. In this phase, the role of the learner is that of an Actor. This phase mirrors Bruner's enactive stage of knowledge representation. As in Bruner's enactive phase, this phase implies that a concept, a process, an event or an object, is understood by the actions a learner performs with it; the mental schema derives from the action and the sensory information. During this phase, it is expected that, through students' physical actions and manipulation of objects, students' conceptual understanding will be grounded in the sensorimotor system. By helping children construct well-organized sensorimotor experiences with computer science concept referents, they are provided with the groundings needed to build the meaning of abstract computer science concepts as these appear later in more formal learning settings.

In the *Formal phase* of our model, activities guide students to formalise actions that are grounded in students' experientially real settings; the aim is for students' actions to be gradually formalised as students recognise the relationships between actions in the previous phases and how these are realised within more formal computing settings (e.g. a programming language's constructs). Activities in this phase include coding with a formal programming language or any other formalisms (a mix of instrumented-symbolic and formal actions) that students need to understand in order to manipulate objects (e.g. Scratch) and thus, the role of the learner is that of an Author .[5]

However, moving from activities that include physical manipulation of objects (Enacted phase) to activities that include formal actions reflected in coding statements to manipulate objects (formal phase) is a huge conceptual step for children. The intermediate stage of the action-concreteness fading process, therefore, should facilitate and scaffold this transition. If the Enacted phase includes physical actions performed on objects, while the formal phase includes formal actions reflected in coding statements, then the intermediate stage should include instrumented actions performed on physical or virtual objects. Instrumented actions scaffold students' actions from concrete to formal manipulations. This argument aligns with the literature presented in section 3.2.1 about physical and digital manipulatives. To reiterate, Tran et al. (2017) argued in favour of digital manipulatives when transfer is considered, and they suggested that concrete manipulatives are better for learning instruction at the beginning, but digital manipulatives are better for transferability. Thus, they postulate that a scaffolding technique that moves students from concrete manipulations to digital could afford the benefits of both representations. Our view does not only focus on the transition from physical to digital manipulatives but highlights this transition in terms of the action performed: from a physical action performed on an object to an instrumented, symbolic and thus, to a more automated or abstracted form of action. As such, during the intermediate stage of the action-concreteness fading effect, instrumented-symbolic manipulations can take the lead to start decontextualising initial representations constructed in the enacted phase and, most importantly, to start automating and abstracting physical actions performed on objects to instrumented-symbolic actions.

The *Instrumented* phase of our model, therefore, is the phase during which the automation of physical actions starts occurring; this is the phase where physical actions are abstracted by the use of instrumented-symbolic actions to perform actions on physical, and virtual objects. The role of the learner in this phase is that of an Issuer-Author depending on the underlying activity (Issuer, when the children experiment with the buttons and other interactive tools to explore their immediate effect, and Author, when the children actually authoring a sequence of actions). Similarly to the previous stage, sensorimotor experiences with computer science concept referents, reciprocal to the ones used in the previous phase, aim to further ground the meaning of abstract computer science concepts and promote transfer to the next phase. Table 1 presents the model in a block-based view and gives examples or descriptions of activities that can be used in each block.

In all three phases of the model, the following processes take place: in line with grounded cognition theorisations, a concept is understood by the actions a learner performs with an object, and thus, the concept's mental schema or representation derives from the action and the sensorimotor information. During all three phases, it is expected that, through children's actions on objects that exist in their physical or virtual environment, children construct well-organized sensorimotor experiences with computer science concept referents; thus, they are provided with the groundings needed to build the meaning of abstract computer science concepts as these appear later in more formal learning settings.

The actions performed in each phase can be seen as an abstraction-action process where concrete physical action referents of CS concepts are gradually abstracted by introducing instrumented-symbolic actions referring to the same concept before fully being replaced by formal actions. In the following subsection, we present in detail an example for teaching the concept of sequences by using this model and adhering to the horizontal (ACF) and vertical (MCF) concreteness fading process.

4.1.3. EIFFEL and design and teaching principles

Having presented the model and what each of the three phases entails, Table 2 summarises the design principles that will guide our future learning trajectories as stemming from the extensive literature presented here, and our model.

Based on these, in the following paragraphs, we hypothesise how the model could be used to teach the concept of sequences for students at early years of key stage 2 (at the age of 7–9 years old – the same activities can be used for younger children but the formal stage should not be taken into consideration). As we have not yet tested the duration over which students should engage with each phase (this is an aim of the next phase of our research), we only describe here two lesson activities for each phase. Many more activities can be used – in what follows we just give an example for each phase of our model.

Table 1. EIFFEL – some *indicative* examples or descriptions.

	Enacted	Instrumented	Formal
	The Actor	The Issuer-Author	The Author
Physical objects	Unplugged activities (e.g. dance)	Activities with digital tools such as Bee-Bot, KIBO	Block based with formalisms and formal coding activities that manipulate objects in the physical environment
Virtual objects	Touch screen activities to manipulate objects	Block-based activities (e.g. ScratchJr)	Block based with formalisms (e.g. Scratch) and other coding activities (formal language)
Mental objects	Activities with gestures	Creating a mental representation from some instrumented instructions and altering/executing them mentally	Creating a mental representation from formal instructions and altering/executing them mentally

Table 2. Design principles.

Dimensions	Focus	Design principles	Teaching guidelines	EIFFEL
Horizontal – ACF	Action and time	Specific type of action referents of computing concepts should engage students for a long period of time	Use specific type of actions through manipulatives consistently over a long period of time	Engage students with each phase of the EIFFEL for a long period of time
	Action fading	Action concreteness should fade away slowly and guide students from concrete to more abstract actions	Begin with highly transparent concrete actions and move to instrumented symbolic and then formal actions over time	Move through the phases of the EIFFEL model for each concept slowly
	Action congruency	The action performed should be semantically related (or integrated) to the learning concept	1. Explicitly explain the relation between the action performed and the underlying concept 2. Avoid irrelevant actions	Activities in each phase of the EIFFEL should be semantically related with the underlying concept
	Action and transfer	Metacognitive prompts facilitate transfer	Use metacognitive prompts to facilitate transfer	Link activities from the enacted, to the instrumented, and then to formal phase by using metacognitive prompts
Vertical – MCF	Manipulative concreteness fading	Manipulative concreteness should fade away slowly	Begin with unplugged activities and/or concrete manipulatives and then move to virtual manipulatives	Within each phase of the model, fade away the concreteness of the manipulative
	Manipulative and transfer	Metacognitive prompts facilitate transfer	Use metacognitive prompts in each activity to facilitate transfer	Link activities within each phase of the model with metacognitive prompts

4.1.3.1. The enacted phase. The first activity in the enacted phase is called unplugged dance and engages students' whole body. The activity describes sequences of steps for performing dance moves. As such, through the whole-body engagement, students enact the concept of sequences (*Action-Congruency dimension*). The aim of this activity is for the students to understand that instructions, in plain English, need to be followed in a sequence for them to execute the dance moves appropriately. At the end of the activity, metacognitive prompts are introduced to help students reflect on their learning (*Manipulative-Transfer dimension*). More unplugged activities could be used should the teacher feels that is needed for enhancing students' understanding (*Action-Time dimension*). In the next activity, the teacher could ask the students to use a touch screen to manipulate and create a sequence of objects according to a corresponding criterion. This time physical actions are to be applied to virtual objects (*Manipulative-Fading dimension*). The teachers could also engage students with other activities that do not pay attention to the design dimensions we listed above, but this would be better done after conceptual understanding has been established. At the end of the enacted phase, the teacher engages students with metacognitive prompts before moving to the next phase (*Action-Transfer dimension*).

4.1.3.2. The instrumented phase. The role of this phase is to start fading away the concreteness of actions that represent the concept of sequences (*Action-Fading dimension*). Whereas in the previous phase, students represent the notion of sequences with their whole body (first activity), in this phase, the actions performed, referents of the sequences' concept, are less concrete than before, and they are symbolic. The first activity in the instrumented phase is called Bee-Bot treasure-chest (another tool that is commonly used is KIBO, Elkin et al., 2016; Sullivan et al., 2015). The aim of the activity is for the students to program the Bee-Bot[6] by applying instrumented-symbolic actions rather than concrete, on a manipulative in the physical environment. Students need to press the right buttons to make the Bee-Bot to follow the instructions that will lead it to the treasure chest located on the ground. Students realise that sequences of instructions are created by pressing the buttons in the right order (*Action-Congruency dimension*). At the end of the activity, metacognitive prompts are introduced to facilitate learning (*Manipulative-Transfer dimension*). Following this activity, students can use Scratch Junior to achieve the same aims but this time, actions are performed on a virtual object (*Manipulative-Fading dimension*). In this activity, students guide the Cat to a treasure chest by placing blocks next to each other. The teacher will include as many activities as needed according to the students' understandings (*Action-Time dimension*). As previously, at the end of each activity the teacher engages students with metacognitive prompts before moving to the next phase of the model (*Action-Transfer dimension*).

4.1.3.3. The formal phase. In the final phase of the model, the aim is again to fade away even more the type of actions that referred to the concept of sequences by including formal actions (*Action-Fading dimension*). In this phase, we have selected activities including the Scratch tool or the Micro-Bit. There are plenty of activities one could design in this case – we suggest here that initially, when the focus is on conceptual understanding, teachers employ few distractors and focus on highlighting how Scratch and its blocks or the Micro-Bit can be used and manipulated (including formalisms) to build a sequence of instructions (*Action-Congruency dimension*). Teachers should create as many lessons as needed for students to realise that a sequence is an order of instructions executed one after the other (*Action-Time dimension*). After that, when students have understood what sequences are about in this phase, more joyful and enriching activities can be used.

In summary, each of the three phases organises students' experiences based on the type of actions performed on physical or virtual objects (thus, it is not the tool per se that belongs to a category but the activity organised with that tool). Starting with the enacted phase, students' conceptualisations are a reflection of physical actions and as such students' conceptual representations are rich with sensorimotor information. The instrumented phase moves students to more orchestrated and symbolic actions performed on physical or virtual objects; actions are still concrete in the sense that students can physically interact with a button or a symbol, but they are more abstract than in the enacted phase – they are symbolic. Finally, students' actions are formal and thus, are represented as formalisms and can act on physical or virtual objects. Each phase contributes to the next and provides the groundings for advancing students' understandings from concrete to more advanced and abstract. Thus, our model suggests that when students are requested to abstract the meaning of computing concepts, the work that has been done in these three phases will have provided students with reasonably efficient and sufficient sensorimotor experiences with CS concept referents, necessary to ground the meaning of abstract CS concepts as portrayed in more formal CS education settings.

5. Discussion and future research

The role of sensorimotor activities in children's cognitive development has long been emphasised in the education literature. In Jean Piaget's theory of cognitive development, for example, the sensorimotor stage sets the grounding of cognitive development and emphasises that children's interactions with the world through sensorimotor experiences constitute the foundations of later representational knowledge. Bruner also advocated three human information processing systems for constructing models of the world: through action, through imagery and language; thus, he recognised three modes of knowledge representation: enactive, iconic and symbolic. In the enactive phase, Bruner highlights the importance of action and the environment in children's cognitive development.

Bruner's account aligns with the accounts of grounded cognition; in computing education, grounded cognition can be traced mostly in the use of unplugged and physical computing activities as we explained in section 3.3. During these activities, students engage in different kinds of actions to enact computing concepts and thus, action is central in the development of early years computing conceptual understandings. Thus, our study capitalises on action as the central process of early conceptual development, and by doing that, it draws from grounded cognition theorisations to suggest a theoretical model for conceptual development in the early years of computing education (EIFFEL). The general premise underlying the model is that programming and computational thinking concepts are first realised as actions performed on physical and virtual objects and, therefore, advancing students' conceptualisations in early years computing education needs scaffolding and abstraction in terms of actions. By students' engagement with unplugged, physical, and early years plugged activities (e.g. ScratchJr) that manipulate objects, children's conceptualisations of computing concepts are constructed through their actions performed on physical or virtual objects.

Overall, our aim in this paper was to present a theoretical model based on grounded cognition theorisations and educational literature on the use of manipulatives which provide a foundation for students' conceptual development in the early years of computing education. Although the model is theoretical in its basis, it aims to set the theoretical groundings for the support of scalable learning experiences in computing education that advance students' conceptualisation of computational concepts. Our next step is to translate our theoretical model to learning trajectories that ensure that computing activities for early years computing contribute to all students' conceptual development in the subject and, thus, facilitate conceptual understanding in computing (e.g. Kallia and Sentance, 2021; Sirkiä & Sorva, 2012; Kallia & Sentance, 2021; Kallia and Sentance, 2017; Brackmann et al., 2017; Kaczmarczyk et al., 2010; Sirkiä, 2012; Shmallo and Ragonis, 2021). These activities will set the groundings of CT concepts which students will more formally experience later in their computing courses. While we have set initial design principles upon which our model is based (sub-section 4.1.3), we need to address further research questions to translate the model to concrete guidelines for computing teachers and these questions can only be answered by empirical research: the time advised for children to spend in each phase of the model, the tools that are most appropriate to bring about conceptual understandings in each phase and how the activities need to be further scaffolded, whether unplugged activities or physical computing activities enhance conceptual understanding and facilitate transfer to the next phase, how metacognitive prompts facilitate transfer, and whether a full cycle of the model's phases is required before students are introduced to a new concept. We also aim to suggest cost-effective tools that can be used as alternatives to each of the phases of the model (e.g. KIBO is an expensive tool that not all schools can apply) to apply the model to higher education settings, but further considerations need to be made regarding both the content of activities and the way these can be part of the undergraduate curriculum.

6. Conclusion

Although grounded cognition theories, and particularly embodied theories, have been widely discussed in disciplines like mathematics, in computing education, until today, there is no conceptual developmental framework for the early years of computing education that can support the theoretical and practical design of learning trajectories based on grounded cognition perspectives. To this end, in this paper, we designed a theoretical model based on a narrative literature review on grounded cognition and education literature. The model (EIFFEL – **E**nacted **I**nstrumented **F**ormal **F**ramework for **E**arly **L**earning in Computing) suggests three phases, Enacted, Instrumented and Formal, and its underlying conceptualisation is that programming and computational thinking concepts are first realised as actions performed on objects; as such, the model aims to contribute to children's conceptual development by scaffolding children's actions from concrete and physical to more symbolic and formal forms of action representation.

The framework constitutes the first attempt to organise a developmental conceptual model in computing education based on grounded cognition perspectives. The ultimate goal of our research is to employ this model and its theoretical underpinnings to develop learning trajectories that can be employed by teachers and curriculum developers to design learning activities that gradually move students' conceptualisations from concrete, situated and multi-modal to formal and more abstract representations.

Notes

1. According to Barsalou (2020), modalities are grouped into two categories: *external perception* which includes vision, audition, haptics, gustation, olfaction and *internal perception* which includes proprioception, interoception, affect, reward, introspection.
2. the system responsible for movement control and organisation of movement.
3. Situated action refers to situations where agents have goals and act. During these situations, agents need both to perform cognitive processes (e.g. goal management, inference, perception, categorisation, reward, assessment, and affect) and also to coordinate them (Barsalou et al., 2007).
4. The topic around the role of whole-body movement and gesturing will not be examined for the purposes of this paper.

5. Our model does not yet address students' engagement with formalisms that do not have a direct and visual impact on physical, tangible or visual objects as it is supposed to address conceptual development in the early computing education.
6. https://www.tts-international.com/bee-bot-programmable-floor-robot/1015268.html.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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