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Review

ICT Skills in the Deployment of 21st Century Skills: A (Cognitive) Developmental Perspective through Early Childhood

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Abstract: ICT technologies are an integral part of today's digitized society. Therefore, it is important that children acquire ICT skills as part of 21st century skills education to prepare them for later life. Drawing on the literature, seven 21st century skills can profit from the addition of ICT skills, i.e., technical, information, communication, collaboration, critical thinking, creative, and problem-solving skills. While many efforts have been made to integrate ICT skills as part of 21st century skills education into primary and secondary school curricula, the implementation of these skills in early childhood education and care remains a challenge due to developmental concerns. This paper aims to uncover developmental antecedents for ICT 21st century skills in early childhood, mainly addressing children's cognitive development, and propose ways to implement these skills in child-friendly ways. Drawing on the literature on developmental psychology, seven cognitive developmental antecedents were identified: inductive, deductive, abductive, causal, and scientific reasoning, executive functions, and computational thinking. Moreover, five additional developmental antecedents were identified: fine motor skills, language development, self-regulation, social-emotional development, and creativity. On the backdrop of these antecedents, ways of implementing ICT skills as part of 21st century skills education in early childhood classrooms are proposed that include digital games and learning apps, collaborative play or problem-solving activities with toy robots.

Keywords: ICT skills; 21st century skills; early childhood education; educational robots; reasoning; cognitive development

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1. Introduction

In their 2012 analysis of frameworks on 21st century skills, Voogt and Roblin [1] concluded that 21st century skills involve a large set of different skills: communication, collaboration, information and communication technology (ICT) literacy, social and/or cultural awareness, creativity, critical thinking, problem-solving, and the capacity to develop relevant and high-quality outcomes. They claim that at the core of all reviewed frameworks on 21st century skills were ICT skills and that these skills were associated with important competencies, such as managing, evaluating, and producing information in digital contexts, i.e., many of which require the cognitive abilities to think, reason, and conclude. ICT skills refer to the skills that are needed in today's digitized society in relation to information and communication technology. A lot of information is transmitted via ICT, so ICT skills are needed and can take effect in digital problem-solving, computer-based assessment, communication at the workplace, and several other contexts of our daily lives [2]. For example, in the Programme for the International Assessment of Adult Competencies (PIAAC), ICT skills were needed to navigate the technology-based administration of the cognition-based problem-solving assessment. Participants had to be able to navigate the platform, switch between pages, select responses, use drag-and-drop, etc., to successfully solve the tasks [3]. Van Laar and colleagues [4] suggest that 21st century skills and ICT skills are interrelated and can take the form of ICT 21st century skills (or 21st century digital skills), i.e., subskills that invite a digital component. They define seven such skills, i.e., technical, information, communication, collaboration, critical thinking, creative, and problem-solving skills. They argue that these skills can be supported using ICT, and ICT skills can be fostered in the context of these 21st century skills. Moreover, cognitive abilities were identified as an important prerequisite for the acquisition of many of these skills [4].

Moreover, as ICT skills are essential in adult life, it is argued that they should be supported in school curricula, and undoubtedly many efforts have been made to integrate ICT skills in the context of 21st century education into secondary and even primary school curricula [5,6]. For example, the Innovative Technologies for an Engaging Classroom (iTEC) project supports technological innovation in 19 European countries, and many governments have made the integration of ICT skills into schools mandatory, often in the context of 21st century skills education (e.g., Australia, Belgium, Ireland, Norway, and South Korea [7]; UK [8]). For example, UK school curricula mandate that primary school children should understand simple algorithms and should be able to solve problems by writing such simple algorithms themselves. Moreover, they are required to acquire technical skills, such as understanding how to handle computers. However, young children who do not yet attend primary or secondary school are often neglected when it comes to providing them with ICT skills. Potential reasons range from the assumption that children younger than 6 years are unable to think in analogies and, therefore, cannot understand the complex processes involved in digital technologies [9] to children's cognitive and physiological development, such as the distinction between 2D and 3D vision, and potential health threats [10] as well as to a deep-rooted societal apprehension when it comes to young children using such technologies at a comparably early age [11]. Arguments against the implementation of ICT skills in early childhood education and care (ECEC; 3 to 5 or 6-year-old children, depending on the country) usually view the use of ICT devices as a threat to children's playful learning and development, e.g., impaired emotional and social development [12]. These notions contrast with the fact that, inevitably, children encounter digital technologies in their everyday lives and engage with them frequently [13]. Therefore, it is of fundamental importance for ECEC that even young children acquire an at least rudimentary understanding of how these digital technologies work, that is, at least a rudimentary level of ICT skills, and that they have the chance to develop the cognitive, social, and emotional skills that are necessary to deal with digital devices and that can be expanded on later in their education [14]. However, often the use of ICT devices in ECEC is seen as an end in itself that neglects children's developmental affordances. Thus, it is essential to carve out developmental antecedents of ICT skills in the context of 21st century education, how they can inform the way ICT skills are implemented in ECEC, and how this implementation can additionally support these early cognitive antecedents.

The reason for this necessity becomes clear when drawing on results from developmental research: early learning and cognitive development, i.e., changes in the abilities to think, reason, and draw conclusions [15], are fundamentally related to understanding and achievement later in life, as the development of a knowledge network facilitates the integration of more sophisticated knowledge in later life [16]. Like ICT skills, many complex cognitive skills are the target of facilitation relatively late in education, but studies have provided evidence that many of these skills can be fostered in early childhood, i.e., in children between 3 to 6 years, if the conditions are developmentally appropriate. For example, Chantal and Markovits [17] found that even 2 to 5-year-old children are able to use deductive reasoning—a process that was long assumed young children could not master—if they are prompted to think about alternative premises and receive a fantasy-story context for easy problem-solving tasks such as generating ideas for a birthday present. Moreover, young children can acquire scientific reasoning skills, such as the variable control strategy [18] and coordination of theory and evidence [19], if they are presented with unconfounded experiments that rely on perfect covariation in a story context. Similarly, young children between 3 to 6 years of age might be able to acquire ICT skills if the conditions in the educational settings are appropriate.

Following these considerations, initial efforts to integrate ICT into ECEC have been made in different countries [8,20,21]. However, implementing these ICT 21st century skills into ECEC faces multiple challenges. (1) Children's education in pre- and primary school requires knowledge about developmental processes. For example, especially in ECEC, the learning environments should rely on tasks with low cognitive demands, which are arguably better suited for young children than the more complex tasks commonly used for older children and adolescents. (2) The learning environments should relate to competencies that build on each other. For example, complex problem-solving skills need to be addressed differently in 5-year-olds compared to 8 or 10-year-olds. For younger children, the problems need to be applied with a low level of complexity [22] but can become increasingly complex and abstract as the children grow older. Angeli and her colleagues [5] proposed a framework to foster five sub-skills of problem-solving using ICT devices (an ICT 21st century skill)—abstraction, generalization, decomposition of problems, algorithmic thinking, and solving mistakes—in three different age groups. They suggest that six-year-old children can acquire algorithmic thinking by first decomposing an easy problem, e.g., programming a robot to navigate through a maze, into subproblems and then specifying a step for each subproblem. Lastly, the steps need to be arranged in the correct order. Older children between the ages of 10 and 12 can use the repetition of steps and might even formulate logical expressions to solve digital problems. Repetition and logical expressions should not be part of ECEC, as children lack the cognitive capacity to formulate these complex solutions. (3) Learning environments need to follow guidelines for developmentally appropriate practice [23]. Thus, efforts to implement 21st century skills into ECEC might even rely on playful approaches, such as collaborative play [24–26].

Building on these considerations, this paper aims to revisit and define developmental antecedents with a focus on cognitive development for ICT skills that young children have already developed, as well as to carve out ways to implement these skills along with fundamental ICT skills into ECEC. These considerations are informed by the literature on children's development and applied educational studies on teaching ICT skills in ECEC.

2. Aims and Method

Based on an extensive literature review on ICT skills, 21st century skills, and (cognitive) development, we aim first to connect 21st century ICT skills, as defined by van Laar and colleagues [4], to the literature on children's development. The main goal of this paper is to uncover antecedents for different 21st century ICT skills. Second, these antecedents can inspire the ways ICT is implemented into ECEC. We suggest educational approaches to implement 21st century ICT skills into ECEC based on developmental considerations.

Our main focus is children's cognitive development since it can inform ways of implementing ICT skills into ECEC. We are, however, fully aware that this is only one part of children's development and other aspects, such as emotional and social development, might also have merit for children's acquisition of ICT skills. Therefore, we address them briefly in Section 4 (possible developmental antecedents), but describing children's full development is beyond the scope of this paper.

The literature search for this opinion paper was conducted between October 2022 and March 2023. The search engines used were Google Scholar, Psyndex, PsycArticles, and PsycInfo.

3. A Definition of ICT Skills in the Context of 21st Century Skills

In order to define and revisit developmental antecedents for ICT skills in young children, a conceptualization of ICT skills in early childhood is needed. One comprehensive way of defining and conceptualizing ICT skills is in the context of 21st century skills, since 21st century skills, by their very nature, are usually applied through the use or the integration of digital technologies. Thus, the use of ICT devices is one form of how information can be accessed, which might influence 21st century skills and can inform how they can be fostered at all ages [3]. Additionally, van Laar and colleagues [4] state that ICT skills and 21st century skills are often viewed as interrelated, but a clear definition of this interrelation is lacking. Thus, the authors suggest seven 21st century skills that invite the addition of a digital component, allowing the support of ICT skills. According to them, (1) Technical skills refer to the basic skills needed to operate digital devices. (2) Information skills encompass the search, evaluation, and organization of digital information [27]. (3) Communication skills include the skills needed for digital social interactions, such as contacting others or sharing information via e-mail, social media, and messenger apps [6]. (4) Collaboration skills regard the skills needed for collaboration in digital environments, e.g., simultaneously working on a document or online project or sharing ideas via messengers [6]. (5) Critical thinking skills involve making informed decisions, which can be achieved by closely analyzing, synthesizing, and evaluating received information [6]. In a digital context, critical thinking entails the skills to quickly filter and assess online information and differentiate between true and fake news through critical assessment of the contents [4]. (6) Creative skills include the development and creation of new ideas with the help of digital tools [28,29]. (7) Problem-solving skills encompass the skills to formulate problems in a way that digital devices can process, search for (multiple) solutions for familiar and unfamiliar problems, and generalize knowledge to new problems [30,31].

These considerations provide a basis for understanding how ICT skills play an important role in the context of 21st century skills. As stated, the ECEC context has three specific challenges that need to be considered. First, a fruitful implementation of ICT skills in ECEC demands knowledge about young children's developmental processes. Thus, cognitive, emotional, and social antecedents need to be addressed. Second, it remains unclear how the implementation of ICT skills can build on these antecedents while also fostering the antecedents adequately. Third, ECEC should be developmentally appropriate [23]. ECEC mostly relies on playful learning [25]. Thus, play might be a way to foster ICT skills in the context of 21st century skills in young children.

4. Possible Developmental Antecedents for ICT 21st Century Skills in Early Childhood

In order to implement ICT skills into ECEC with regard to 21st century skills, knowledge of the underlying developmental antecedents is crucial. Unfortunately, few studies have investigated antecedents in early childhood, and more research is needed. This chapter aims to carve out these antecedents for the seven ICT 21st century skills proposed by van Laar and colleagues [4]. The antecedents were inferred from the literature on early childhood development. In particular, we drew on studies on children's reasoning as the search for causalities plays a fundamental role in children's cognitive development and informs skills and competencies such as problem-solving [32–35]. An overview is presented in Table 1. Moreover, all research papers included in this paper are presented in Table 2.

Table 1. 21st century skills and their possible developmental antecedents.

Possible Developmental Antecedents	21st Century Skills [4]	ICT Skills in Young Children
Inductive reasoning	Technical skills Information skills Critical thinking skills Problem-solving skills	Induct rules by uncovering commonalities between devices, categorizing new information through exploration of virtual spaces, and drawing conclusions from gathered information about devices, digital games, etc.
Deductive reasoning	Technical skills Information skills Critical thinking skills Problem-solving skills	Transfer and generalize knowledge of one device to another, generalize information gathered from virtual spaces, use logic to solve (digital) problems step by step

Table 1. *Cont.*

Possible Developmental Antecedents	21st Century Skills [4]	ICT Skills in Young Children
Abductive reasoning	Technical skills Information skills Critical thinking skills Problem-solving skills	Infer rules and regularities about devices and digital games, explain inconsistencies, formulate ideas to solve problems
Causal reasoning	Information skills Critical thinking skills Problem-solving skills	Search for underlying reasons in virtual spaces, e.g., when gathering information, playing computer games
Scientific reasoning	Critical thinking skills	Formulate hypotheses, gather information, and make informed decisions about received information or games
Executive functions	Information skills Collaboration skill Problem-solving skills	Focusing on important details, shifting attention, inhibiting automated responses during (collaborative) problem-solving, e.g., using robots to solve problems together with other children
Computational thinking	Problem-solving skills	E.g., using robots to solve problems, computer games, sequencing, debugging
Fine motor skills	Technical skills Creative skills	Use of ICT devices, e.g., playing games, using learning apps, digital drawing
Language development	Information skills Communication skills	Using ICT to communicate with others (words, rhymes, songs, etc.), e.g., video-chatting or talking to a family member or a friend, searching for information virtually with the help of AIs
Self-regulation	Information skills Collaboration skills	Regulate search for information in virtual spaces, regulating emotions while using ICT devices together with peers
Social-emotional development	Communication skills Collaboration skills	Using ICT devices in groups of children or with a friend, e.g., using robots to solve problems
Creativity/divergent thinking	Creative skills	Using ICT devices to produce something new and original (e.g., a drawing)

4.1. Inductive Reasoning

Inductive reasoning is concerned with inferring theories and categories from singular cases and rules. There have been many studies on young children's ability for inductive reasoning, and their main results are that children are able to make inductive inferences if they can rely on typicality, similarities, and underlying causal reasons for induction. For example, Gelman and Coley [36] found that 2-year-old children rely on typicality for induction. In their study, children were more likely to determine that a typical bird (e.g., a chickadee) lived in a nest just like the example bird, a robin, than an atypical bird (e.g., an ostrich).

Concerning similarities, Lawson and Fisher [37] discovered that children younger than 8 years draw inferences from similar samples instead of diverse ones. In their study, children were confronted with evidence from samples of mammals that were either homogenous or diverse. Then, children were provided with more evidence on samples of mammals, vertebrates, and invertebrates. The children drew more inductive inferences the homogenous samples than from diverse ones, indicating that young children fail to see the value of diversity for induction.

Underlying causal relations support inductive reasoning as well. In one study, Hayes and Thompson [38] found that children were more likely to make inductive inferences about fantasy animals with causally related features than fantasy animals with causally unrelated features. Similarly, in a study by Opfer and Bulloch [39], children were more likely to use causal relations than perceptual similarity for inductive inferences. However, in the absence of causal information, children relied heavily on perceptual similarity for induction. Goddu and her colleagues [40], as well as Namy and Gentner [41], came to similar results on children's reliance on perceptual similarities in the absence of causal information.

Inductive reasoning can inform 21st century technical, information, critical thinking, and problem-solving skills (Table 1). First, induction can help children uncover commonalities between different digital devices and support their *technical skills*. Second, for *information skills*, children can use typicality, similarity, and causal relations to categorize new information into existing categories or develop new ones [42]. Taking children's development into consideration, provided information, e.g., when learning about different animals in digital settings, should either be typical (e.g., a robin instead of an ostrich), similar (e.g., a robin and a chickadee) or have underlying causal relations that the children can infer (see causal reasoning) or are communicated to them (e.g., nocturnal animals tend to have large eyes so they can see in the dark). Third, *critical thinking* relies in part on inductive reasoning. Reasoning processes such as inductive reasoning are inherent to critical thinking [43] as children use the information they have to determine and judge underlying reasons or concepts. For example, they might conclude that a game is rigged from losing a game after they should have won multiple times. Last, inductive reasoning has strong relations to *problem-solving skills*, as children induct rules to solve problems [44].

4.2. Deductive Reasoning

Deductive reasoning refers to the inference of features or characteristics from a category or a theory to singular cases. Young children face problems with deductive reasoning, even though developmentally speaking, this is already integrated earlier in many children's education. Indeed, studies found that children can apply deduction under certain circumstances. For example, the results of a study by Markovits and Thompson [45] suggest that 6-year-old children can draw conditional inferences if the degrees of freedom are small enough. In their study, children received a conditional statement (if A, then B), followed by two questions (You see A, is B certain? and You see B, is A certain?). Most children correctly agreed that if you see A, then B is certain and rejected the second question as false. In another study on 2 to 5-year-old children by Chantal and Markovits [17], children were prompted to think about alternative ways to solve different problems or received an inhibition task. Afterward, they were confronted with conditional inferences. Children who had been prompted to think about alternatives were more likely to apply deductive reasoning than children who had received an inhibition task.

Deduction relates to the ICT 21st century skills proposed by van Laar and colleagues [4] (Table 1). Deductive reasoning can help children transfer their knowledge of one ICT device (e.g., a tablet) to another (e.g., a computer) and thus relates to their *technical skills*. Concerning *information skills*, children can acquire new knowledge by generalizing information [34], e.g., if an animal is nocturnal, they have large eyes. Owls have large eyes, so they must be nocturnal. Moreover, *critical thinking* also relies on deductive reasoning [43], allowing children to deduce from their concept of cheating that a computer game might be rigged. Last, deductive reasoning plays a critical role in *problem-solving* by using logic to solve problems step by step, with each step being derived from a previous one [46].

4.3. Abductive Reasoning

Abductive reasoning refers to inferring rules and regularities. Abduction can introduce new principles in the process of creating explanations for causal inconsistencies [47,48]. For example, children will search for alternative explanations, i.e., an abductive process, if their causal understanding is violated, e.g., they lost a game even though they should have won. Bonawitz and colleagues [49] found that 5 to 7-year-old children infer rules and look for alternative explanations when their intuitive theories about physical principles are violated. Children showed more explorative behavior if the provided evidence suggested that their theories were wrong, suggesting that they tried to find underlying regularities. Moreover, in a series of studies with 4 to 9-year-old children, Pine and her colleagues reached similar results, suggesting that children can adapt their theories on physical principles under different circumstances that violate their theory [50–55].

Young children's abductive reasoning can support their *technical skills* by the inference of rules and regularities for ICT devices (Table 1). For example, children might infer the rule that touch screens of smartphones light up at skin contact, but a password is needed to unlock most smartphones. Moreover, abduction informs *information skills* when children are confronted with causal inconsistencies and try to infer rules explaining these inconsistencies [48]. For example, children might have inferred that all birds can fly. However, when they come across a penguin, they may realize that their assumption was wrong and search for a rule that explains this inconsistency, e.g., all birds have feathers. As with other forms of reasoning, *critical thinking* also relies on abduction [43]. Building on the example of a rigged game to foster children's critical thinking, children might explore the game's regularities and rules to find out why they keep losing. Last, children may use abductive reasoning while they *solve problems*. They might formulate ideas on how to solve the problem and test these ideas [56].

4.4. Causal Reasoning

Causality is at the heart of children's development, and children rely on causal reasoning even in infancy [32,33]. Children from the age of 3 years can transfer causes across domains if they understand the underlying reason for the causality [57]. Kushnir and Gopnik [58] discovered that children between 4 and 6 years draw causal conclusions from co-occurrences, while even two-year-old children can infer causal relations from patterns of variations and covariation [59]. Furthermore, 4 to 5-year-old children can infer causal relationships between multiple categories [60]. Moreover, 5 to 7-year-olds draw causal conclusions from their intuitive theories about their physical [49,61] and biological surroundings [62].

Children's *information skills* rely on causal reasoning ([32]; see Table 1). Causality helps children acquire new information and supports other cognitive processes, such as forming and adapting categories [63,64]. Thus, providing children with underlying reasons or supporting them in inferring these reasons might help them acquire information, e.g., nocturnal animals have large eyes because they help them capture what little light (moonlight) can be seen at night. Moreover, children's *critical thinking* can profit from their causal reasoning skills as they search for underlying reasons if they are confronted with inconsistencies [43]. Thus, they might simply determine that the computer game they keep losing at is rigged, which is the underlying reason for their failure to win. However, children struggle to view new evidence as separate from prior beliefs, especially when they have to combine different sets of evidence, which might hamper their critical thinking as well as their *problem-solving* [65]. Therefore, problems should be presented in a familiar setting with limited degrees of freedom.

4.5. Scientific Reasoning

Scientific reasoning encompasses the processes of hypothesizing, variable control, and coordination of theory and evidence [18,66]. Ruffman and colleagues [19] found that children between 4 and 5 years of age can formulate hypotheses if they are confronted with perfect covariation. Moreover, van der Graaf and colleagues [18] discovered that 4 to 6-year-olds can apply the variable-control strategy and thus conduct unconfounded experiments if they are taught to do so. Additionally, children in the same age group realized when an experiment they set up had been confounded by an experimenter and refused to draw conclusions from the experiment [67]. Lastly, children between 3 and 6-years of age are able to coordinate theory and evidence if they are confronted with perfect covariation but face problems with imperfect covariation [68–72].

Scientific reasoning might inform children's *critical thinking*, as they actively formulate hypotheses of why they keep losing at their game, change their behavior when playing again to find evidence and coordinate the produced evidence with their hypotheses (Table 1). Young children will likely face problems with such a complex task and will need support from a teacher or caregiver [35].

4.6. Executive Functions

Executive functions encompass working memory and the processes of shifting attention and inhibition [73,74]. In early childhood, working memory relates to the ability to store and process information. Shifting describes the ability to change the focus of attention and switch between tasks or strategies. Moreover, inhibition refers to the suppression of automated responses or thoughts [73,75].

Studies suggest that the development of executive functions is most pronounced in the preschool years [76]. Three and four-year-old children face trouble with tasks that require executive functions, while from the age of five, children typically perform well [73,77–79].

Regarding 21st century skills (Table 1), executive functions can help children acquire new *information* through selective attention and their working memory. They can help children *collaborate* with others by supporting them to focus on relevant details of the collaborative process. Similarly, they are predictive of young children's *problem-solving skills* by aiding the inhibition of irrelevant information, keeping in mind relevant information, and shifting the attention to important details [80,81]. For example, they play a role in ICT problem-solving activities with robots [78].

4.7. Computational Thinking

Problem-solving in the digital context is often referred to as computational thinking [82]. Angeli and colleagues [5] define five competencies needed for computational thinking, abstraction, generalization, decomposition of problems, algorithmic thinking, and solving mistakes (or debugging). Studies show that preschool children can apply computational thinking in different contexts [83]. For example, in a study by Di Lieto and colleagues [78], 5 and 6-year-olds solved small problems with child-friendly, programmable robots. Similarly, a guided programming activity with an adult's support can increase computational thinking skills in young children [84]. Moreover, in their systematic review on computational thinking in ECEC, Bati [85] found that children from 3 years of age onwards are able to apply computational thinking and that this ability improves with age, mainly due to limited working memory capacities in younger children.

Computational thinking is an important part of the 21st century *problem-solving skill* (Table 1). Supporting young children's computational thinking—abstraction, generalization, decomposition of problems, algorithmic thinking, and solving mistakes—can be implemented in applied and uncomplex settings [22], such as the story context used in the study by Di Lieto and colleagues [78].

4.8. Fine Motor Skills

Fine motor skills comprise skills that rely on small muscle movements, such as manipulating small objects [86], e.g., smartphones or educational robots. Children need fine motor skills to use touchscreens, which makes them important for their *technical skills* when handling ICT devices. Research on the effects of early tablet use in preschool children has been mixed. While there are some results suggesting that tablet use by children between 4 and 6 years hampers their fine motor skills development compared to children who never use tablets [87], another research group has found that 2 to 3.5-year-old children who use tablets develop their fine motor skills faster [88]. In both studies, fine motor skills were defined as skills that rely on small muscle movements, such as the manipulation of objects. In addition to technical skills, children's fine motor skills might interact with the 21st century skill of *creativity*. Creativity in young children is often expressed through drawing [86], and ICT devices such as whiteboards can be used for that purpose [28]. Drawing is a part of fine motor skills, and the use of ICT for creative processes might not only benefit fine motor skills but also support them. However, the question of the interaction of fine motor skills development with ICT devices remains yet unanswered.

4.9. Language Development

By preschool, children have acquired a large vocabulary [89]. Three- to four-year-olds acquire new words by eye gaze, linguistic or intentional information [90], using a wide range of information to broaden their vocabulary. Language is one basis for *communication*, making it an important tool for communication using ICT devices. Furthermore, children can use language to speak about ICT devices with their parents, teachers, sibling, or peers. Moreover, to acquire *information* with ICT devices, spoken language is paramount in most instances, especially for young children who cannot yet read or write. Advancements in technology allow young children to ask questions to artificial intelligence, such as Siri, Cortana, or Google Assistant and receive answers.

4.10. Self-Regulation

Zimmerman [91] defines self-regulation as the ability to initiate and adapt behavioral processes based on self-observations. Whitebread and colleagues [92] assume that preschool children already possess the ability to control their cognitive processes, and other studies point in that direction as well [93]. Self-regulation might be related to information and collaboration skills. Thus, it can help guide the search for new *information* and help children realize that they might be lacking knowledge. Moreover, self-regulation might help children navigate potential negative situations that can arise during *collaboration* by regulating their behavior and emotions.

4.11. Social-Emotional Development

Darling-Churchill and Chipman [94] describe young children's social and emotional development as the ability to form and keep relations with others and express emotions appropriately. Studies show that 4-year-old children can adapt that language to their interaction partner, suggesting social and emotional competencies [95]. Social-emotional competencies such as empathy and emotional regulation can help young children to *communicate* and *collaborate* with their caregivers and peers effortlessly.

4.12. Creativity/Divergent Thinking

Children's creative development is investigated in several ways by many researchers. However, a consensus on what constitutes creativity has not been reached, and multiple models of creativity that highlight the importance of process, person, and product have been posed [96]. Most theories agree that creativity can be expressed in everyday situations [96,97] and in early childhood can take the form of drawing, handicraft, making up songs, pretend play, etc. [98]. Creativity is a multifaceted construct that encompasses, depending on the theoretical underpinning, novel ideas, lateral and divergent thinking, as well as connecting ideas or concepts in new and unconventional ways [99,100]. The most studied creative skill is divergent thinking, i.e., the skill to react with multiple ideas to a stimulus [101]. Studies show that divergent thinking starts to develop in the preschool years [102], and a case study suggests that the use of digital games can potentially foster 3 to 6-year-old children's divergent thinking skills [103]. Therefore, supporting children's *creativity* with ICT devices might support their creative development [28,99].

Table 2. Studies reviewed.

Article	Year	Topic	Location	Sample	Assessment Method	Outcomes
Ali et al. [99]	2019	Creativity	Not explicitly stated	51; 6–10 years	Torrance Test of Creative Thinking	Engaging with robots can support creativity
Angeli and Georgiou [84]	2023	Computational thinking	Europe (not specified)	171; 5–6 years	Observation	Engaging with robots can support computational thinking
Behnamnia et al. [103]	2020	Creativity	Malaysia	7; 3–6 years	Case study	Digital games and learning apps can support creativity
Bijvoet-van den Berg and Hoicka [102]	2014	Creativity	UK	Study 1: 24; 3–4 years Study 2: 16; 2 years	Unusual Box test	Children differ in their divergent thinking and divergent thinking increases with age
Bonawitz, Ullman et al. [60]	2019	Causal reasoning	USA	Study 1a: 78; 4–5 years Study 1b: 20; 4–5 years Study 2: 28; 4–6 years	Observation	Children can make causal inferences between multiple categories
Bonawitz, van Schijndel et al. [49]	2012	Causal reasoning	USA	Study 1: 126; 4–7 years Study 2: 51; 6–7 years Study 3: 32; 6–7 years	Observation	Children infer rules and look for underlying causalities
Chantal and Markovits [17]	2017	Deductive reasoning	Canada	Study 1: 32; 3–5 year Study 2: 32; 2–5 years	Observation DCCS task	Children can use deductive reasoning if they are prompted to think about alternatives
Croker and Buchanan [72]	2011	Scientific reasoning	UK	144; 3–11 years	Interview Observation	Prior knowledge and causality play a role in children's scientific reasoning
Di Lieto et al. [78]	2017	Executive Functions Computational Thinking	Italy	12; 5–6 years	Pippo says Backward Corsi Block Tapping NEPSY-II	Children can solve problems with a child-friendly robot
Gelman and Coley [36]	1990	Inductive reasoning	Not explicitly stated	Study 1: 22; 2–3 years Study 2: 2.5–3 years	Interview	Children use typicality for induction
Goddu et al. [40]	2020	Inductive reasoning Causal reasoning	USA	Study 1: 48; 3–4 years Study 2: 48; 3–4 years Study 3: 48; 3–4 years Study 4: 36; 3–4 years	RMTS task PowerPoint stimuli	Children rely on causal inferences instead of perceptual ones

Table 2. *Cont.*

Article	Year	Topic	Location	Sample	Assessment Method	Outcomes
Gopnik et al. [59]	2001	Causal reasoning	USA	Study 1: 38; 3–4 years Study 2: 16; 30 months Study 3: 24; 3–4 years	Blicket detector	Children rely on causality for categorization
Hayes and Thompson [38]	2007	Inductive reasoning	USA	Study 1: 72; 5, 8–9 years Study 2: 64; 5 and 9 years Study 3: 144; 5, 8–9 years Study 4: 72; 5, 8–9 years	Interview	Children use perceptual similarities and causality for induction
Kandlhofer et al. [104]	2016	AI-assisted learning	Switzerland	24; 4–6 years	Observation, video data	AI can support children's creativity
Köksal-Tuncer and Sodian [69]	2018	Scientific reasoning	Germany	67; 3–6 years	Observation	Children can systematically test hypotheses
Koerber et al. [68]	2005	Scientific reasoning	Germany	Study 1: 76; 4–6 years Study 2: 33; 5–6 years	Prior Belief and Evidence tasks	Children have a basic understanding of hypothesis-evidence-coordination
Kushnir and Gopnik [58]	2005	Causal reasoning	USA	Study 1: 19; 4 years Study 2: 18; 4 years	Observation	Children draw causal conclusions from co-occurrences
Kushnir and Gopnik [67]	2007	Scientific reasoning	USA	Study 1: 61; 3–4 years Study 2: 32; 3–5 years Study 3: 16; 3–5 years Study 4: 36; 3–4 years	Observation	Children realize if experiments are confounded and do not draw conclusions from them
Lawson and Fisher [37]	2011	Inductive reasoning	USA	Study 1: 30; $M = 4.7$ years Study 2: 15; $M = 5.1$ years Study 3: 30; $M = 4.9$ years Study 4: 30; $M = 5.0$ years	Interview	Children draw inductive inferences from similar examples but not diverse ones
Lin [87]	2019	Fine motor skills	Taiwan	72; $M = 61.9$ months	BOT-2	Tablets hamper children's fine motor development
Markovits and Thompson [45]	2008	Deductive reasoning	Studies 1 and 2: UK Study 3: Belgium	Study 1: 56; 6–8 years Study 2: 53; 6–9 years Study 3: 26; 7 years	Interview	Children can draw deductive inferences if few degrees of freedom are presented

Table 2. *Cont.*

Article	Year	Topic	Location	Sample	Assessment Method	Outcomes
Namy and Gentner [41]	2002	Inductive reasoning	USA	Study 1: 24; 3–5 years Study 2: 40; 4–5 years	Interview	Children use perceptual similarities for induction unless they have prior knowledge
Nurmsoo and Bloom [90]	2008	Language development	USA	64; 2–4 years	Observation	Children learn new words by eye gaze, linguistic or intentional information
Opfer and Bulloch [39]	2007	Inductive reasoning	Not explicitly stated	Study 1: 64; 5–7 years Study 2: 32; 4–7 years	Digital testing procedure	Children rely on causalities for induction
Piekny et al. [70]	2014	Scientific reasoning	Germany	138; 4–6 years	Interview	Children's understanding of experiments increases between 5 and 6 years
Piekny and Maehler [71]	2013	Scientific reasoning	Germany	223; 4–13 years	Interview	Children can differentiate conclusive from inconclusive experiments
Pine et al. [50]	2007	Abductive reasoning	Not explicitly stated	21; 6–7 years	Video data	Children use gestures to express their theories rather than spoken language
Pine et al. [51]	2004	Abductive reasoning	UK	140; 5–9 years	Video data	Gestures imply representational change in theories
Pine and Messer [55]	2000	Abductive reasoning	UK	140; 5–9 years	Video data	Children change their theories if they receive explanations about regularities
Pine and Messer [52]	2003	Abductive reasoning	UK	25; 5–6 years	Observation	Children change their theories if their theories are violated
Pine et al. [53]	1999	Abductive reasoning	UK	42; 4–7 years	Video data	Children infer regularities through trial and error
Pine et al. [54]	2002	Abductive reasoning	UK	126; 5–7 years	Video data	Children infer rules from observation
Relkin et al. [83]	2020	Computational thinking	USA	768; 5–9 years	TechCheck	Children can apply computational thinking
Ruffman et al. [19]	1993	Scientific reasoning	UK	Study 1: 32; 4–5 years Study 2: 54; 5–7 years Study 3: 18; 6–7 years	Interview	Children can formulate hypotheses when confronted with perfect covariation

Table 2. *Cont.*

Article	Year	Topic	Location	Sample	Assessment Method	Outcomes
Schmidt et al. [75]	2022	Executive functions	Germany	88; 3–6 years	EF touch battery BRIEF-P Effortful Control Scale	Self-regulation and executive functions are related
Schulz et al. [62]	2007	Causal reasoning	USA	Study 1: 80; 3–5 years Study 2: 36; 4–5 years Study 3: 40; 4–5 years	Interview	Children draw conclusions from biological casualties
Senn et al. [81]	2004	Executive functions	USA	117; 2–6 years	Delayed alternation Shape School Spatial reversal Tower of Hanoi	Inhibition is a strong predictor of problem-solving
Shatz and Gelman [95]	1973	Social-emotional development	USA	16, 3–5 years	Video data	Children adapt their language to their interaction partner
Sobel and Munro [57]	2009	Causal reasoning	USA	Study 1: 32; 3 years Study 2: 40; 3 years Study 3: 25; 3 years Study 4a: 25; 3 years Study 4b: 16; 3 years	Observation	Children can transfer causes across domains if they understand the underlying reason for the causality
Souto et al. [88]	2020	Fine motor skills	Brazil	28; 2–3 years	Bayley III	Tablet use supports fine motor skills
Van der Graaf et al. [18]	2015	Scientific reasoning	Netherlands	183; 4–6 years	Observation	Children can learn to use the control of variables strategy
Venitz and Perels [93]	2019	Self-regulation	Germany	53; 5–7 years	Video data	Adult support does not increase children's self-regulation
Verdine et al. [79]	2014	Executive functions	USA	44; 3–5 years	Tap Test Flexible Item Selection Task	Executive functions predict mathematics performance
Weber et al. [61]	2020	Causal reasoning	Germany	183; 5–6 years	Interview	Children can understand causalities through play
Whitebread et al. [92]	2009	Self-regulation	UK	1440; 3–5 years	Video data	Children can control their cognitive processes

Table 2. *Cont.*

Article	Year	Topic	Location	Sample	Assessment Method	Outcomes
Williams et al. [105]	2019	Creativity (among others)	USA	80; 4–6 years	Questionnaire, Assessment	Toy robots can foster children's creativity
Zelazo, Müller et al. [77]	2003	Executive functions	Canada	Study 1: 41; 3–4 years Study 2: 16; 3–4 years Study 3: 20; 3–4 years Study 4: 48; 3–4 years Study 5: 16; 3–4 years Study 6: 48; 3–4 years	DCCS	Children from the age of 5 perform well on executive function tasks; inhibition depends on experience

5. Implementing ICT Skills into ECE

Efforts to introduce ICT skills in ECEC have been made, and there is some research on ECEC teachers' perceptions of ICT and ICT skills and their implementation [20]. Often education entails the simple use of digital tools instead of an analogue equivalent, e.g., [28]. While this simple use of digital tools might be exciting and, in the short term, motivating for the children, it remains questionable how digital tools can be used in a meaningful way to support children's 21st century skills or even their learning of traditional skills, such as language and STEAM (science, technology, engineering, arts, and mathematics).

Suggestions for K-12 education include the implementation of computer science as a mandatory school subject. However, this approach is not feasible for ECEC due to administrative and educational issues, such as the already limited and much-needed play time in early childhood classrooms and lacking knowledge of ECEC teachers [25]. Indeed, ECEC is characterized by child-centeredness. However, the use of ICT can undermine this child-directedness if the teachers fail to implement them adequately. For example, whiteboards are seldom used interactively in ECEC. Instead, teachers use them for instruction [106], and in effect, ECEC becomes less child-centered. On the other hand, Plowman and Stephen [107] found that the promotion of ICT skills in ECEC mainly contains leaving the children free to play with digital technologies without any guidance from teachers. However, leaving children to play with ICT devices without any guidance can lead to demotivation on the part of the children and hamper their learning [25]. Without guidance or high amounts of guidance bordering on direct instruction, the simple use of ICT devices is unlikely to support children's acquisition of ICT 21st century skills. Consequently, Kerckaert and colleagues [25] found that ICT can be used as a means, e.g., to foster 21st century skills as well as children's development, or a subject to foster ICT skills.

Drawing on studies from children's developmental antecedents and the literature on ICT 21st century skills, we suggest possible learning opportunities on the basis of constructivist approaches that can be implemented into ECEC, and that can be administered in the context of playful learning or digital play [26,108]. Fostering these 21st century skills in ECEC on the backdrop of children's development is not only desirable for children's further learning and development but also gives early ICT literacy education a purpose apart from only being an end in itself. The seven skills described by van Laar and colleagues [4] can be implemented into ECEC by employing simple, non-complex tasks and measures fit for young children.

5.1. Technical Skills

Technical skills might be supported by allowing children to handle digital devices, such as tablets or laptops, in a protected setting with a teacher present and able to intervene when necessary. The technologies used should be developmentally appropriate, e.g., suitable for young children's reasoning skills and fine motor skills development. For example, children can play a game on a tablet or use a learning app; they can use a whiteboard for drawing or play with child-friendly robots together with other children or a caregiver [26]. These are tools that children can handle motorically [28,84,88]. Moreover, they can induce possible underlying commonalities of the different ICT devices, e.g., every device needs to be switched on, and transfer that knowledge to new devices they might not yet have had the chance to engage with. Lastly, they might infer specific rules for different devices, e.g., devices with a touchscreen or without a touchscreen. ECEC teachers can support these activities by highlighting similarities, typicality, and differences. With that, children can learn the basics of handling different types of technologies through inductive, deductive, and abductive reasoning. This skill is closest to the way that ICT skills are often practiced, as in ECEC [20].

5.2. Information Skills

The rise of new technologies provides children the opportunity to use ICT devices to explore virtual objects or spaces, e.g., in games [26], and to interact and directly ask questions to artificial intelligence (AI), such as Siri, Cortana, or Google Assistant with the help of a caregiver. There is vast information for children to be discovered in child-friendly online spaces. Teachers can ensure that the information the children encounter, e.g., in a game or a learning app, is presented in a way that young children can understand, e.g., the application is language-free or important details are provided in spoken language.

Indeed, AI-assisted education is on the rise in ECEC. For example, Williams and colleagues [105] found that a toy robot can be a learning companion for children between 4 to 6 years. For more in-depth analyses of AI-assisted learning and AI literacy, a scoping review by Su and Yang [109] and an analysis on the integration of AI in ECEC by Su and Zhong [110] are available.

The information presented should contain typical, similar, or causally related examples to facilitate induction, the inference of regularities, and the inference of underlying causalities [32,37–39,48]. Moreover, children's deductive processes and thus their generalization might be supported by providing few degrees of freedom [45], e.g., in a quiz with a limited set of answer alternatives. This is especially important regarding young children's limited working memory capacity, i.e., a limitation in their executive functions [85]. A quiz might also serve the purpose of helping children realize if they are lacking information and encourage them to acquire it, supporting their self-regulation.

5.3. Communication Skills

Spoken language is one of the main tools for communication in young children, and they can use this form of communication with ICT devices as well, which might foster their digital communication skills. According to van Laar and colleagues [4], digital communication skills encompass appropriate and effective communication using digital means, such as e-mail and instant messengers. While young children do not communicate in these ways, the familiarization of using ICT devices to communicate in child-appropriate ways may support early prerequisites that later and more complex digital communication skills can build upon. However, the idea of young children communicating digitally with others might make people uncomfortable [11], and surely, oversight by a caregiver is essential. Many young children already communicate with others, e.g., they might use their parents' smartphones to call or video-chat with their grandparents together with their parents. ECEC teachers might use these experiences as an opportunity to spark a discussion and provide explanations about the advantages, disadvantages and even dangers of communicating using digital devices [111].

5.4. Collaboration Skills

Supporting collaboration skills can easily be intertwined with the support of other ICT 21st century skills, such as creativity and problem-solving. For example, children can collaborate with their peers using digital devices, e.g., by painting together on a whiteboard [26]. Moreover, there is a wide range of easily accessible problem-solving activities to choose from online, e.g., solving problems with child-friendly robots [112].

Similar to collaboration in non-digital settings, collaboration with ICT devices might help children acquire social-emotional competencies, such as emotional regulation. To address children's general limitations in their executive functions, collaborative activities should make it as easy as possible to focus on the relevant details of the collaborative process [73,85], e.g., having few degrees of freedom in the chosen activity to prevent frustration. Thus, a collaborative problem-solving activity might consist of a simple problem with a single solution, e.g., a robot should take the fastest route from point A to point B. By employing ICT devices to support collaboration, children can familiarize themselves with the setting. This might facilitate their acquisition of further digital collaboration skills in more complex ICT environments that they will encounter later.

5.5. Critical Thinking Skills

Addressing critical thinking skills in ECEC might be the most challenging task since 21st critical thinking skills rely heavily on logic [4]. One way to prepare children for a world flooded with fake news that they might later encounter in online spaces might be to provide children with relatively obviously false information, e.g., claiming that dices are round or that cats bark and dogs meow or have them play a simple but rigged computer game with easy rules. Children might then reject these statements or question the fairness of the game, and the teacher can encourage them to defend their conclusions. Especially for young children, false information should relate to things they are familiar with [22], e.g., cats and dogs. Children might use their own or a neighbor's pet for reference (induction), draw on their concepts of cats and dogs and the differences between the two (deduction), refer to the rule that dogs bark (abduction), and might even provide causal explanations, even if they are not valid. The teacher might then encourage the children to gather more information to test whether the child or the teacher is correct and help them coordinate their theory with the evidence they found [69]. With this, children can be supported to recognize false information that they might encounter later in online spaces.

5.6. Creativity

The idea of fostering creative skills in digital environments has been implemented in different ECEC programs and studies [21,28,99,103,113]. For example, drawing tools for children can be implemented, and various providers, e.g., TATE UK (https://www.tate.org.uk/kids, accessed on 1 April 2023), have a special online offer for children. Results of studies with older children as well as case studies in preschools suggest that play with ICT devices, e.g., with social robots [99] or digital games and learning apps [103], can support children's fluid capacity to handle ideas as well as their divergent thinking. Moreover, creativity skills might be fostered during problem-solving activities, as divergent thinking can help come up with new ideas and solutions [101]. Furthermore, Kandlhofer and colleagues found that the use of AI tools in ECEC can also foster children's creative thinking [104]. Concerning children's development, creative activities such as drawing might support children's fine motor skills and creative skills.

5.7. Problem-Solving Skills

Fostering digital problem-solving skills in ECEC can take the form of computational thinking education. Young children can solve problems that are applied and have conditions that are familiar to the children. One such problem could be that a robot should move from point A to point B. This problem can be made more complicated for older children by adding more variables, such as finding the fastest route or avoiding certain spatial points. Many simple problems involving ICT devices are available online [112,114].

If the problems are applied and have few degrees of freedom, children will find it easier to infer rules, solve problems step-by-step, come up with ideas on how to solve the problem and integrate new evidence into the problem space [17,45,65]. Furthermore, especially for young preschool children between 3 and 4 years of age, problems with shifting, working memory, and inhibition can arise [80]. Thus, fewer degrees of freedom also serve the purpose of facilitating problem-solving for young children as their executive functioning will not be overloaded.

6. Limitations

Since covering all aspects of children's development in great detail is beyond the scope of this paper, we mainly focused on their cognitive development. Other similarly important aspects, such as emotional, social, and motivational development, could only be addressed superficially. Children's brain development as an overarching factor influencing every aspect of children's development—be it cognitive, emotional, or social—was not investigated either. The examination of brain development and its effect on ICT 21st century skills could be a promising opportunity to advance the field. The focus on cognitive development limits our findings and suggestions to a singular but influential part of children's development. Indeed, designated papers focusing on the interplay of ICT skills with different developmental aspects are needed, and our paper may function as a starting point to investigate these aspects in more detail.

Moreover, many of the 21st century skills are investigated in large research areas of their own. This is particularly the case for critical thinking, creativity, and problem-solving. Various theoretical and methodological approaches are implemented in these research areas, and covering them all is beyond the scope of this paper. Nevertheless, this paper synthesized multiple studies from developmental and educational psychology, underpinning key competencies that young children can acquire. With that, the paper contributes to the definition of (cognitive) antecedents in young children of these important 21st century skills and the ways they can be implemented in ECEC.

7. Conclusions

Fostering ICT skills in ECEC should be developmentally appropriate and can be combined with the support of early 21st century skills if it is done against the backdrop of children's development. This paper proposed ideas on how this difficult endeavor can be accomplished.

For the inclusion of ICT 21st century skills in ECEC, three challenges were addressed. (1) Children's development needs to be considered. Since covering all aspects of children's development would have been beyond the scope of this paper, we mainly focused on their cognitive development. Multiple antecedents that are vital for children's use of ICT and their ICT skills were uncovered in this paper. From a cognitive perspective, reasoning skills play a crucial role, but other non-cognitive skills, such as motor and social-emotional development, can inform possible implementations of ICT 21st century skills in ECEC and future research. (2) Children should acquire early ICT 21st century skills that can be built upon later in their education. In this paper, we proposed seven skills following van Laar et al. (2020) and suggested possible ways to lay the foundation for these important skills in ECEC. (3) The implementation should be developmentally appropriate and thus can take place in playful, child-centered settings with child-friendly ICT devices and with the guidance of ECEC teachers. In conclusion, this paper can inform future research on developmental antecedents of ICT 21st century skills and on ways to lay the foundation for these skills in ECEC.

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