Review and Discussion of Children's Conceptions of Computers

Michael T. Rücker, Niels Pinkwart

accepted manuscript

The final publication is available at `link.springer.com`
DOI: `10.1007/s10956-015-9592-2`

Today's children grow up surrounded by computers. They observe them, interact with them and, as a consequence, start forming conceptions of how they work and what they can do. Any constructivist approach to learning requires that we gain an understanding of such preconceived ideas and beliefs in order to use computers as learning tools in an effective and informed manner. In this paper, we present five such conceptions that children reportedly form about computers, based on an interdisciplinary literature review. We then evaluate how persistent these conceptions appear to be over time and in light of new technological developments. Finally, we discuss the relevance and implications of our findings for education in the contexts of conceptual pluralism and conceptual categorisation.

1 Introduction

Today's children grow up surrounded by computers. They observe them, interact with them and, as a consequence, start forming conceptions of how they work and what their basic capabilities are. Thus, children will arrive in our classrooms with more or less sophisticated ideas about these devices, which naturally influences their interactions and learning in contemporary computerised classrooms.

In the context of computer science education, Pea (1986) was among the first to identify various programming misconceptions, and he proposed the idea of a "superbug," a more fundamental misconception regarding the general capabilities of the machine, which he identified as the root cause for many of the problems plaguing his novice programmers. More recently, Sorva (2013) has conducted an extensive review of student misconceptions in programming and also addresses the issue of conceptions related to the underlying machine that actually executes the code. Computers have long since moved beyond the CS classroom and have become essential tools for teaching and learning in numerous other subjects. In the context of a constructivist approach to learning, it is clear that using these tools in an effective and informed manner requires that we gain an understanding of students' preconceived ideas and beliefs about them.

However, it is a very challenging task to investigate such fundamental conceptions of computers, given the rapid change and development of new technologies and modes of interaction. The ways we interact with computers today have almost nothing in common with those of 60, 40 or even 20 years ago. We are not dealing with conceptions regarding relatively stable theoretical constructs, but constantly evolving human-made artefacts. Thus, it is not even clear whether any such conception can indeed persist for a longer period of time.

In this paper, we present a literature review to assess the current state of research on children's conceptions of computers. In Sect. 2 we briefly discuss the terminology and methodology of our review process. In Sect. 3, we present five distinct conceptions that we were able to identify based on our review. In Sect. 4 we then discuss how persistent these conceptions appear to be, that is, how much they appear to be influenced by new technological developments. We also address two points that we regard as central for any fruitful application of these findings to educational practice. Section 5 concludes the paper with a brief summary and outlook.

2 Terminology and Method

This paper is concerned with children's ideas and beliefs about how computers operate, what they are made of, and what their intrinsic capabilities are. Apart from established dictionaries, a broadly accepted definition for *computer* is surprisingly hard to find. Brunjes (1977) asked the question "What Is a Computer?" and concluded that

> no current definition will ever truly define what a computer is because computers continually grow and change. [...] Experience will provide the best definition of all, or, if not a definition, at least an understanding, which is really more important! (p. 85)

In light of ongoing research on biological or quantum computation, Brunje's statement from nearly four decades ago seems almost prophetic. Nevertheless, we feel that conducting a transparent literature review requires that we at least provide a working definition, if only to give the reader a chance to object. So for the time being, we will aim to use the term *computer* in a rather inclusive sense to denote any device – electronic or otherwise – that can be instructed to automatically execute computations. Such a definition has to be used cautiously, nevertheless, and we will return to it in Sect. 4.3.

To denote people's mental representations, ideas and beliefs about a particular phenomenon or artefact, two prominent terms are found in the literature: *concept* and *conception*. However, the former is also sometimes used to denote allegedly objective representations of what something *really* is (cf. Weiskopf 2009, p. 149 for a discussion). Obviously, the mental representations of interest here are not of such an objective kind.

Thus, we will refer to them as *conceptions* throughout. Related terms are *preconception* and *misconception*, which are commonly used to denote people's erroneous or unscientific conceptions.

Another relevant term in this context is *mental model*. A general definition of it, however, is almost impossible to obtain, as it is used differently in different contexts and fields. See Jones et al. (2011) for an interdisciplinary survey and synthesis attempt. It is often unclear where exactly the line between *mental model* and *conception* should be drawn. Franco et al. (1999) suggest that they exist on different levels of abstraction but are nevertheless often interdependent. Hence, research on children's mental models of computers, specific computer processes or larger computer systems may also provide valuable insights into related overarching or underlying conceptions.

A preliminary search on the subject revealed that the relevant literature is dispersed across multiple fields of research, without a common terminology or publication forum. Consequently, we did not a priori limit our search to certain databases, publication formats or even research fields, which is usually common practice in systematic literature reviews. We judged such a strict approach to be unsuitable to capture the majority of the relevant literature in this case.

Instead, we employed an iterative procedure. We started out with various search terms, like *conception*, *conceptualisation* or *mental model*, which we combined with terms like *computer* or *technology*, and entered them into various search engines, like available library catalogues, Worldcat and Google Scholar. This led to an initial set of relevant publications. From there, we started to traverse those publications' cite graphs. That is, for each publication, we looked at the literature it cited and used systems like Google Scholar and Web of Science to find publications that cited it. This led to more relevant findings and, occasionally, additional search terms, like *intelligent artefact*, that we had not considered previously. We reiterated this process until, eventually, it stopped yielding any new relevant findings.

Naturally, most publications discovered in that way were ultimately not considered relevant to our interest. Determining a publication's relevance consisted of two steps. The first was a rather superficial survey including only the respective title and abstract. In most cases, this was enough to determine that a publication did not cover a topic relevant to our interest. Such publications were not included in further iterations of the search. In particular, the majority of the literature on misconceptions in CS education, which primarily focusses on specific algorithmic constructs or data structures (e.g., Kolikant 2001; Eckerdal and Thuné 2005; Sanders et al. 2006), was discarded in this step.

The second step was performed after the search had been completed and involved reading the full text. In doing so, we looked for explicit descriptions of conceptions by the respective authors. Subsequently, we read the articles again and looked for further, implicit evidence for these conceptions in the other accounts. This revealed that still many of the remaining publications did not contain findings relevant to our interest. This included, in particular, normative assessments of students' prior knowledge (e.g., Simon et al. 2006; Hammond and Rogers 2007) or purely statistical word analyses (e.g., Oleson et al. 2010).

Source	Background	Int.	Omn.	Mech.	Wire	Prog.
Wolfe 1968	Math. Educ.	X	X	X		
Mawby et al. 1984	CS Educ.	X	X	X	X	X
Turkle 2005	Psych./Sociol.	X		X		X
Hyson and Morris 1986	Dev. Psych.	X				
Hughes et al. 1987	Dev. Psych.	X	X		X	X
Denham 1993	Dev. Psych.				X	
Scaife and van Duuren 1995	Dev. Psych.	X				
van Duuren and Scaife 1995	Dev. Psych.	X				X
van Duuren and Scaife 1996	Dev. Psych.	X				
van Duuren et al. 1998	Dev. Psych.		X			X
Jervis 2003	Tech. Educ.				X	
Jervis 2005	Tech. Educ.			X		X
Papastergiou 2005	CS Educ.		X			
Bernstein and Crowley 2008	Cogn. Psych.	X				
Levy and Mioduser 2008	Tech. Educ.	X				X
Diethelm et al. 2012	CS Educ.		X			

Table 1: Overview of evidence found in reviewed publications.

We considered reliable findings, those conceptions, for which evidence could be found in at least three different publications. Conceptions such as "all computers are giant machines" (Wolfe 1968, p. 38) or that there is a "chemical that can make the computer work" (Hyson and Morris 1986, p. 22) were thus considered artefacts. The final result was a set of five conceptions, which we will present in the following section. The corresponding evidence is contained in 16 publications: ten journal articles, three conference papers, one technical report, one book chapter and one monograph, which cut across various research disciplines, including education, developmental psychology and sociology. Table 1 provides an overview and indicates the respective evidence they contain.

3 Children's Conceptions of Computers

3.1 Computers are Intelligent

The conception that computers are intelligent, thinking or even conscious entities is arguably the most widely researched and reported in the literature. Generally speaking, it includes attributing to the computer some form of mind or brain (human or otherwise) as well as various mental states like motivations, intentions or even emotions. The computer is often anthropomorphised and seen as some kind of living entity that is better understood in terms of psychology rather than technology.

Wolfe (1968) presents one of the earliest accounts of this conception. He presents a sample of quotes by seventh-grade children with virtually no prior computer experience whatsoever, illustrating their ideas and beliefs about this technological novelty. Many of the quotes are indicative of a conception that computers can think and the author concludes that some children seemed to believe that "[c]omputers are 'smarter' than men" (p. 37) and that the "computer is a replica of a man's brain" (p. 38).

Over a decade later Mawby et al. (1984) conducted individual interviews with 20 children aged eight to twelve. When asked how a computer works, several made references to a brain or mind. The authors conclude that many children were unsure whether computers can think and to what extent this thinking is similar to human thinking.

Turkle (2005), in her seminal 1984 publication, makes very similar observations. She studied over two hundred children, aged four to fourteen and reports that they often disagreed and discussed about the mental capabilities of computers and whether they are truly alive. However, regardless of what answer they finally arrived at, their discourse about computers was predominantly psychological rather than physical, including aspects like intelligence, intentions, motivations and consciousness (pp. 48-49). Further, she observed that the more the children interacted with computational devices, the more elaborate and nuanced their psychological discourse about them became (pp. 51-52).

Hughes et al. (1987) conducted semi-structured interviews with over one hundred children, aged 6 to 12, on two different occasions 16 months apart. Among other things, they asked the subjects whether they thought computers could think, remember, want something or do things by themselves. In accordance with Turkle, they found that the number of positive answers to these questions significantly increased from the first to the second interview occasion. Interestingly though, on both occasions there were no significant differences between the age groups. This suggests that the observed effects are not due to children's cognitive development but rather due to their increased experience with computers, as over the 16 months between the two interviews, home computer access among the subjects "rose from 7% to 40%" (p. 29).

In a series of studies, van Duuren and Scaife further investigated whether and to what extent children attribute various mental states and cognitive features to computers and robots. An analysis of written stories by 230 children aged 7 to 11 and 38 adults showed that subjects at all ages were prone to describing computers and robots in terms of animate and intelligent behaviour (van Duuren and Scaife 1995). In two other studies, the authors investigated children's willingness to attribute a brain as well as various brain-related items like thinking, dreaming or remembering to a person, a computer, a robot and a doll. It was found that with increasing age (from 5 to 11), children became more likely to make such attributions to the computer and robot (Scaife and van Duuren 1995; van Duuren and Scaife 1996). Unfortunately, none of the studies were controlled for prior computer experience or usage.

In fact, more recent findings by Bernstein and Crowley (2008) support the hypothesis that computer experience is a relevant factor. The authors presented 60 children, aged 4 to 7, with various entities, including a calculator, a computer, a humanoid robot and a rover, and asked subjects to rate them with respect to their biological and intellectual properties. The ratings were found to be independent of age, but positively correlated with prior experience.

The lack of prior experience could thus explain the findings reported by Hyson and Morris (1986). The authors conducted interviews with 15 4-year-olds who had little to no prior experience with computers, and report that "[t]he majority of children did not believe that a computer can talk, get sick, go to sleep, or even think" (p. 24).

Taken together, these findings clearly suggest a developmental trend. Children who have had very little first-hand contact with computers are initially undecided as to whether they can think for themselves or not. As they become more engaged with the artefacts' capabilities, their cognitive features become more and more salient and children's discourse about them thus becomes more and more psychological, up to the point where they may even grant them a certain status of aliveness. At some point, however, a line is drawn between the artefacts and living human beings. Here, Turkle (2005) suggests that this line is drawn on the basis of emotion: computers can think, but only humans can feel. Another approach to draw this line is by means of a computer's programmability: computers can or have to be programmed, humans have free will (cf. Sect. 3.5).

Regarding the epistemological origins of this conception, Turkle (2005) argues that children are by no means averse to physical explanations (see also Sect. 3.3 below). However, while other things like bicycles or wind-up cars can eventually be understood in terms of gears and springs, computational artefacts are simply too opaque, too mentally challenging to be understood in physical terms. "But children do not lack intellectual curiosity or inventiveness. They turn to a way of understanding where there is more to say–that is, a psychological way of understanding" (p. 62). This argument is consistent with the observation that usage and experience rather than age correlate with children's conceptualisation of computers as intelligent. Unless one is actually confronted with computers, there is little incentive to analyse and explain their behaviour.

Levy and Mioduser (2008), in a small study with 6 children, aged 5 to 6, specifically investigated what explanatory frames they used when analysing a robot's behaviour. The authors report that, with increasing task difficulty, children became more likely to use psychological explanations instead of technological ones.

The behaviour of computational artefacts can be very complex and unpredictable – just like that of living beings. And just as it is virtually impossible (not only for children) to explain the behaviour of living beings in terms of neural activity and muscle contractions, it is equally futile to try and explain the behaviour of computational artefacts in such physical terms. A psychological framework provides concepts like intentions, motivations and beliefs, which in turn provide a means to analyse and discuss not only the complex behaviour of humans, but also that of computers.

3.2 Computers are Omniscient Databases

This conception can essentially be summarised as: computers know everything, and they know everything by heart. The computer is seen as a giant database containing a seemingly infinite amount of information, including the answers to virtually all questions. Consequently, it does not really compute anything at all. It just stores and retrieves data.

Again, some of the earliest pieces of evidence for this conception can be found in the quotes reported by Wolfe (1968). The author summarises that some children apparently believed that "[c]omputers contain in memory [...] most of the facts known to man" (p. 37), and that, if you had a problem, "you just 'ask' the computer for the answer" (p. 38).

Hughes et al. (1987) report on children who asserted that computers would know about crimes being committed or the current whereabouts of relatives. On the first interview occasion, "[t]he most commonly mentioned 'good things' about computers were that they 'help you' or 'tell you things' (45 mentions)" (p. 18).

The following comment by Mawby et al. (1984) is especially telling:

> Too often, [children] spoke as if computers know specific facts, such as the product of 23 times 45, rather than having general algorithms that generate specific answers to specific questions. Many of the younger children seemed almost to view the computer as a natural object, which "just knows" things and has the intrinsic ability to answer questions. (p. 30)

This question of whether children think computers produce answers by computation or by just retrieving it from memory was further investigated by van Duuren et al. (1998). The authors conducted two studies, the first of which we will discuss in Sect. 3.5. In their second study, they asked 20 adults and 60 children, aged 5 to 11, how they thought a computer had produced the result of a mathematical calculation. It was found that 40 percent of the 8-year-olds and 45 percent of the 11-year-olds thought the computer had had the answer already stored in memory, whereas none of the 5-year-olds apparently thought so.

Work by Papastergiou (2005) illuminates the issue from a different angle. She conducted a study with 340 students, aged 12 to 16, regarding their mental models of the Internet. The results show that a total of 214 students (∼63%) seemed to believe that a single computer – either the user's own or a remote one on the network – stores the entire Internet (pp. 347-9). The author concludes that many students apparently believed "that the capacity of a computer's storage media is unlimited" (p. 349). Diethelm et al. (2012) also report on students' conception of the Internet as "one big central computer" (p. 72).

In summary, there exists considerable evidence, albeit mostly indirect, that some children are prone to conceptualising computers as essentially giant databases. The storage capacities of computers are seen as unlimited and thus offer at least the potential for storing and retrieving every piece of information in existence. Consequently, a single computer might very well store the entire Internet, while others may simply know the answers to virtually all questions, without the need to actually compute anything.

3.3 Computers are Mechanical

The conception of computers as mechanical devices pertains to their basic hardware configuration, i.e, how they are built: with gears, springs and levers. The inner workings of a computer are thus seen more like an intricate clockwork. Data and processes exist as physical entities inside the computer. They move around and are stored in physical places.

Reported evidence for this conception is scarce, but it exists. Again, one of the earliest accounts can be found in Wolfe (1968), where one of the children described how a computer works by way of "[m]echanical hands" that move information around and literally "write on the card" (p.36).

Mawby et al. (1984) also present several children's quotes that are indicative of a conception of computers as mechanical, likening them to a clockwork in which "each part moves a different part" (p. 12), or using terms such as "engines" (p. 18), "machinery" (p. 20), or "little gears" (p. 32). Interestingly, some of these seemed to be blended with a conception of computers as intelligent such that it is the mechanics that enabled the computer to think. A similar blend can be found in Jervis (2005), where a child asserted in an interview: "[they think] with little gears" (insertion in the orig., p. 10).

Turkle (2005) proposes a plausible argument for the epistemological origin of this conception. She argues that many other devices and toys that children interact with, e.g., wind-up cars or bicycles, can indeed be understood in mechanical terms, in terms of moving parts, gears and springs. "Children try to use the same kind of reasoning with computer toys and computers. They try to understand how these work in physical terms. But this turns out not to be so simple" (p. 61). In their frustration, her argument continues, children eventually turn to a psychological frame of explanation (cf. Sect. 3.1). However, many mechanical devices like wind-up watches, cash registers or typewriters have pretty much gone extinct over the last decades. They have been replaced by computers. It may have been exactly these devices that children knew from their everyday lives and that provided a source of inspiration for their conception of computers as mechanical. So it is, in fact, questionable whether Turkle's argument is still valid today.

In summary, reported evidence of children conceptualising computers as mechanical devices is rather scarce and is mainly found in older sources, the only exception being the study reported by Jervis (2005). Given the above argument, it is indeed questionable whether there is still a mentionable number of children today who conceptualise computers in terms of mechanical parts.

3.4 Computers are Wire Networks

Under this conception the computer is seen as a network of different components, e.g., chips, batteries, memory units or even various fantasy elements, which are linked together, usually by wires or tubes. The links can either be systematic or form a completely untraceable tangle. The central aspect is that components are connected somehow. The components themselves are often of lesser import. They largely remain black boxes. It is their connections that determine the computer's capabilities or functions.

Many of the quotes reported by Mawby et al. (1984) include references to wires as the primary components of a computer's internal make-up (pp. 18,19,31). Again, some of them are examples of conceptual blends such that computers "connect wires to make it think" (p. 32), or that programming means "putting wires together" (p. 9).

Hughes et al. (1987) also report that, being asked how a computer works, a "substantial number mentioned various electrical components, such as wires (27 mentions), electricity (16), batteries (9) and plugs (6)" (p. 24). Several also mentioned tapes, memory units or microchips, which had recently been introduced in class. How exactly children might have conceptualised the connections between these components, however, cannot be reconstructed from the authors' descriptions.

Findings reported by Denham (1993) are more informative in this respect. In a series of three studies, the author analysed children's drawings of the inner workings of computers. The first two were a pilot study involving 38 children about the age of 12, and a replication of the pilot with 132 children, aged 9 to 12. Subjects were asked to imagine themselves shrinking in size and entering a computer through one of its rear ports. "The question posed was 'What would you expect to see when you stood up and looked around?'" (p. 349) The produced drawings featured very similar components to those mentioned above. "By far the most significant were communication/links, transport, memory, and input/output (I/O) functions" (p. 349). Furthermore, older subjects were more likely to represent structured connections, whereas younger ones tended to employ a disorganised "'muddle' of wire" (p. 351). The third study introduced constraints to the task. It involved 122 children aged 9 to 12, who were "asked to imagine themselves programming the computer to print their name on the screen" (p. 351). Again, wires, tubes and transmission links were the most frequent means by which children conceptualised the letters arriving on the screen, sometimes with a stopover at a memory unit.

Jervis (2003) also analysed children's drawings of the internals of computers, in a study with 26 7-year-olds and 26 11-year-olds. Again, wires were found to be central elements in many of the produced drawings, and a substantial number "resorted to 'tangled wires' as a metaphor" (p. 15).

In general, the specific expression of this conception seems to be heavily influenced by children's prior knowledge of computer components. Younger children simply may not have heard of "chips" or "memory units." But they probably do know about electricity, about batteries and mains connections, and they know that electricity runs through wires. A plausible reasoning thus might go as follows: since computers are very complex electronic devices, they have to have some very complex wiring inside. What exactly is wired to what, however, initially remains a complete mystery, a tangle. As children grow older and acquire more knowledge about the components inside a computer, they incorporate this knowledge into their existing conception. The wires start to disentangle as they now connect specific components. Eventually, the components may even take on the dominant role as the wires are demoted to mere passive information transmitters. If, when and how children actually reach that tipping point, however, remains an open question.

3.5 Computers are Programmable

In its most essential form, this conception can be described as follows: the behaviour and capabilities of computers are determined by humans and can be changed by humans. What these capabilities are and how exactly one goes about changing them can, in turn, be constrained by another conception of computers. However, this is not necessarily the case.

Turkle (2005) discusses programming in the context of children's early attempts to understand the origins of a computer's capabilities. One 7-year-old explained: "People tell it everything. They put ideas into the machine" (p. 56). And an 8-year-old described a "special 'feelings cassette,'" which would enable a computer to have emotions

(p. 56). Again, we find examples of blends: computers *think* or *feel* by virtue of their *programming.* It is the origin of their capabilities, whatever those may be. Turkle (2005) compares this to children's developing conceptions of animacy and aliveness:

> In all of this talk about the machine's origins, children are struggling to develop the idea of an "outside push" for psychological activity much as they struggle to develop the distinction between inside and outside pushes for physical motion. (p. 56)

According to Turkle (2005), this distinction between "inside" and "outside" pushes can ultimately form the basis for the distinction between people and computers.

Findings reported by van Duuren et al. (1998) support this. In their first study, involving 20 adults and 60 children aged 5 to 11, the authors presented the subjects with a film featuring four robots that were controlled by humans, and a fifth identical robot with a seemingly autonomous behaviour. The authors then investigated to what extent children were able to identify the robots' loci of control as external or internal. They found that while 5-year-olds were largely unable to distinguish the different types of robot, the locus of control became a more salient feature for children with increasing age. Furthermore, those subjects that did distinguish between the two types of robot were asked to justify this distinction. It was found "that the majority of subjects in the oldest age groups who differentiated robot No. 5 from Nos. 1-4 also had an understanding of the programmable nature of robots" (pp. 877-8).

This would indicate a certain developmental trend, which can also be found in the findings reported by van Duuren and Scaife (1995). The authors analysed children's stories about computers, robots and bicycles, and found that, with increasing age, subjects became more likely to include words like "program" or "programming" in their stories.

It would seem that, as children grow older, they gradually come to understand that a computer's capabilities are not inherent in the machine itself, but bestowed upon it by people in an act called programming. It is not clear, however, whether children develop such a conception entirely on their own. In the above-cited study by van Duuren and Scaife (1995), some of the older children, who were most likely to use terms like "program" or "programming" in their stories, had had actual first-hand programming experience. Observations by Hughes et al. (1987, p. 24), Jervis (2005, pp. 20-23) and Levy and Mioduser (2008, pp. 352-3) also suggest that children rarely come up with the idea of programming by themselves. Hence, it may very well be that children need to actually engage in programming or at least have to be told about it in order to start conceptualising computers as programmable devices.

Furthermore, the way in which children conceive of programming itself is a somewhat complex matter in its own right. Where programming is seen as the origin of a computer's capabilities, it is, of course, closely connected to the conception of a computer as a whole. We have already given examples of blends, where programming was conceived of as "putting wires together" (Mawby et al. 1984, p. 9), or as inserting a "feelings cassette" (Turkle 2005, p. 56). However, other conceptions, seemingly unrelated to any particular conception of a computer, have also been reported (Thuné and Eckerdal 2010). Furthermore, Mawby et al. (1984) observed that children sometimes tended to overextend the act of programming to include "anything entered into the computer at the keyboard" (p. 10).

We shall not discuss the issue of various conceptions of programming in more detail here. Suffice it to say that having a conception of computer programming – whatever it may be – would seem to require a conception of a computer as something that can be programmed. Humans can, and often must, tell the computer what to do. It is humans who determine the computer's capabilities and functions. Therefore, the concept of programming gives humans a certain control over the computer. Conceptually, it has the power to demote the machine to a mere machine.

4 Discussion

4.1 Persistence and Change

Depending on what aspects of a computer they are concerned with, the conceptions presented in the previous section can be divided into two categories: *intrinsic capabilities* and *internal hardware*. Accordingly, the conceptions of computers as intelligent entities or omniscient databases describe their intrinsic capabilities, i.e., what computers can do. The conceptions of computers as mechanical devices or wire networks describe their internal hardware, i.e., what computers are made of. The conception of computers as programmable then sits at the intersection of these two categories, as a computer's programming determines its capabilities (e.g., thinking or knowing), which might involve changing its hardware components (e.g., connecting wires).

With respect to persistence, both the amount and respective publication dates of the reported evidence suggest a difference between these two categories (cf. Table 1). Evidence for the internal hardware conceptions is rather scarce and, with the exception of the two studies published by Jervis (2003; 2005), is at least 20 years old. In contrast, evidence for the intrinsic capabilities conceptions is somewhat more common and is also found in more recent accounts. This would suggest that conceptions related to the internal hardware of computers are less persistent than those related to their intrinsic capabilities.

Epistemologically, this is extremely plausible. In Sect. 3.3 we have already argued how the disappearance of mechanical devices from our everyday lives may have affected children's conceptions. Furthermore, computational devices keep shrinking in size which makes it increasingly difficult to imagine them containing numerous wires, gears or levers. In contrast to their physical appearance, however, their theoretical capabilities have stayed the same. Computers still do what they have always done: they compute. If anything, their practical capabilities have converged on the above conceptions. Modern computers indeed appear increasingly intelligent and omniscient, as they learn to understand and speak natural language and are able to retrieve virtually any piece of information from vast online databases.

4.2 Plurality and Context

Throughout Sect. 3 we have already given several examples of conceptual blends, that is, of coherent combinations of two different conceptions. This implies that those conceptions are not mutually exclusive, but can, in fact, coexist within a single individual. Other authors have argued for such conceptual pluralism elsewhere, and emphasised that the selection or emergence of any specific conception is highly dependent on context or current communicative goals (Mortimer 1995; Weiskopf 2009; Dawson 2014).

For computers, such conceptual pluralism is extremely plausible. Proudfoot (2011), for instance, criticises AI researchers who refer to their own artificially intelligent creations as if they were indeed alive and thinking. However, it would appear somewhat presumptuous to think that they would not *also* be capable of thinking and speaking about these artefacts in terms of their programmable nature, their storage capacities or their various intercommunicating hardware components. They simply would do so in different contexts and for different purposes. Thus, following the arguments of Mortimer (1995), experts may, in fact, posses very similar conceptions as children. The only difference may be that they are more aware of them and their respective limitations, and are thus more competent in choosing the right one for a particular context (pp. 274-5).

Making students aware of their conceptions and reflect upon their respective advantages and limitations is thus a key aspect of teaching within a pluralist conceptual framework (Mortimer 1995). In order to do this in an informed manner, however, research first needs to identify contexts in which these conceptions are relevant or problematic. For instance, it is undeniable that conceiving of computers as intelligent and thinking entities provides a powerful means to analyse their complex behaviour (cf. Sect. 3.1). However, in the context of programming, this very same conception may present a learning obstacle (Pea 1986). Similarly, regarding computers as essentially omniscient databases is certainly adequate and useful in many everyday situations such as looking up things on Wikipedia or finding a nearby restaurant. Yet, it may lead to misconceptions when learning about computer networks (Papastergiou 2005; Diethelm et al. 2012). Investigating the relevance of these conceptions in other contexts certainly appears to be a worthwhile goal.

4.3 Conceptual Categorisation

In Sect. 2 we have defined *computer* as any device that can be instructed to automatically execute computations. Consequently, the studies reviewed here include various devices like robots (van Duuren and Scaife 1995), electronic toys (Turkle 2005), rovers and calculators (Bernstein and Crowley 2008), and of course desktop computers (Mawby et al. 1984; Denham 1993). Still, most of these studies were conducted at a time that predates the invention of many modern types of computer, e.g., smartphones, tablets, many gaming consoles or modern household appliances. However, it is exactly those types that are increasingly dominant in children's everyday lives. Desktop computers, in contrast, appear to be in decline. In Sect. 4.1 we argued that conceptions related to a computer's intrinsic capabilities appear rather stable and insulated against new technological developments. However, it does not immediately follow that these conceptions also *apply* to all these new developments.

What is needed here is an understanding of children's conceptual categorisation of computers, i.e, which devices they actually conceive of as being computers and are thus eligible targets for their related conceptions. Hyson and Morris (1986) reported that children were quite able to distinguish computers from non-computers, "generally using the keyboard as the defining attribute" (p. 23). Today such an approach would obviously be too restrictive. Indeed, findings by Mumtaz (2002, p. 165) suggest that today's children apply more complex reasoning. What exactly those reasoning processes look like, however, remains unclear. Findings by Jarvis and Rennie (1996) suggest that they might be highly inconsistent.

Research in the cognitive sciences has shown that people can take a variety of properties into account when determining the category status of artefacts, e.g., form, current function, originally intended function, or causal relations between such properties (Malt and Sloman 2007). In addition, artefact categorisation may, again, be highly context-dependent such that there commonly exist multiple ways to categorise an artefact (Houkes and Vermaas 2013). Indeed, many modern devices are computers only in a secondary sense. Their primary functions and uses are those of a refrigerator, a car or a TV-set, and that is exactly what they are called in most everyday situations. To our knowledge, there exists no empirical research investigating if and when children, or laypeople in general, think about the various devices that surround them not only in terms of their primary functions, but also in terms of their computational nature. Obviously, any existing conception of computers could only apply in the latter case.

On a parenthetical note, such research could also help inform classroom practices in a more direct way. An often expressed, albeit rather broad, objective of CS and technology education is to enable students to identify and understand the various computational systems in their environment (e.g., Tucker et al. 2003, p. 3; ISTE 2007; Department for Education, UK 2013). This implies that students, among other things, should be able to do precisely what we have described above, that is, to look beyond an artefact's primary function and, if applicable, recognise it as a general-purpose computational device. Investigating the related conceptual categories could thus reveal how and how well students are actually able to do so and provide insights into how this ability might be improved through education.

5 Summary and Conclusion

In this paper, we have presented five conceptions that children reportedly form about computers, based on an interdisciplinary literature review. Accordingly, computers can be seen as intelligent entities that are best understood in psychological rather than physical terms. They can also be seen as unlimited and potentially omniscient databases, which know the answers to virtually all questions, without having to actually compute anything. They can be seen as a complex network of wires and communication links in which the actual components might play a negligible role. They can be seen as containing a complex mechanical contraption. And they can be seen as programmable machines that need to be told what to do by their human masters.

However, not all of these conceptions appear to be equally persistent over time. While the conceptions related to a computer's intrinsic capabilities (i.e., thinking and knowing) have persisted for nearly half a century now, the conceptions related to a computer's internal hardware (i.e., wires and mechanics) seem to be more easily influenced by new technological developments and may even have disappeared completely by now. Epistemologically, this is very plausible. The physical appearance of computers has changed drastically over the last few decades, while their theoretical capabilities have remained the same. If anything, modern computers do indeed appear increasingly intelligent and omniscient.

Finally, we have addressed two points that we regard as central for any fruitful application of these findings to educational practice. First, it has to be assumed that an individual may hold several conceptions simultaneously, which may or may not be selected in a given context or situation. While a conception may be useful and appropriate in some contexts, it may cause problems in others. Education needs to take this into account and make students aware of such advantages and limitations, which obviously requires that we first gain an understanding of them ourselves. Second, it is unclear to what degree the findings presented in this paper can be generalised to more recent computational devices like smartphones, tablets or modern household appliances. In order to answer this question, research needs to investigate, which things children actually categorise as computers and what cognitive processes are involved when they do.

References

Bernstein, Debra and Crowley, Kevin (2008). "Searching for Signs of Intelligent Life: An Investigation of Young Children's Beliefs About Robot Intelligence." In: *Journal of The Learning Sciences* 17.2, pp. 225–247.

Brunjes, Shannon (1977). "What Is a Computer?" In: *Journal of Medical Systems* 1.1, pp. 79–85.

Dawson, Chris (2014). "Towards a conceptual profile: Rethinking conceptual mediation in the light of recent cognitive and neuroscientific findings." In: *Research in Science Education* 44.3, pp. 389–414.

Denham, Pearl (1993). "Nine- to fourteen-year-old children's conception of computers using drawings." In: *Behaviour & Information Technology* 12.6, pp. 346–358.

Department for Education, UK (2013). *National Curriculum in England: Computing programmes of study: key stages 1 and 2.* URL: `https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239033/PRIMARY_national_curriculum_-_Computing.pdf` (visited on Nov. 12, 2015).

Diethelm, Ira, Wilken, Henning, and Zumbrägel, Stefan (2012). "An investigation of secondary school students' conceptions on how the Internet works." In: *Proceedings of the 12th Koli Calling International Conference on Computing Education Research.* ACM, pp. 67–73.

Eckerdal, Anna and Thuné, Michael (2005). "Novice Java programmers' conceptions of object and class, and variation theory." In: *ACM SIGCSE Bulletin*. Vol. 37. 3. ACM, pp. 89–93.

Franco, Creso et al. (1999). "From scientists' and inventors' minds to some scientific and technological products: relationships between theories, models, mental models and conceptions." In: *International Journal of Science Education* 21.3, pp. 277–291.

Hammond, Michael and Rogers, Philip (2007). "An investigation of children's conceptualisation of computers and how they work." In: *Education and Information Technologies* 12.1, pp. 3–15.

Houkes, Wybo and Vermaas, Pieter E. (2013). "Pluralism on Artefact Categories: A Philosophical Defence." In: *Review of Philosophy and Psychology* 4.3, pp. 543–557.

Hughes, Martin, Brackenridge, Ann, and Macleod, Hamish (1987). "Children's Ideas About Computers." In: *Computers, Cognition and Development: Issues for Psychology and Education*. Ed. by J. Rutkowska and C. Crook. 1st ed. Wiley. Chap. 1, pp. 9–34.

Hyson, Marion C. and Morris, Sandra K. (1986). "'Computers? I love them!': Young children's concepts and attitudes about computers." In: *Early Child Development and Care* 23.1, pp. 17–29.

ISTE (2007). *ISTE Standards: Students*. Tech. rep. International Society for Technology in Education. URL: `https://www.iste.org/docs/pdfs/20-14_ISTE_Standards-S_PDF.pdf` (visited on Nov. 12, 2015).

Jarvis, Tina and Rennie, Léonie J. (1996). "Understanding technology: the development of a concept." In: *International Journal of Science Education* 18.8, pp. 977–992.

Jervis, Alan (2003). *Children's Thinking About Computers*. Paper presented at the British Educational Research Association Conference, Heriot-Watt University, Edinburgh.

– (2005). *'It's Good for Plgging-in a Budgie': Children Talking About Computers*. Paper presented at the British Educational Research Association Annual Conference, University of Glamorgan.

Jones, Natalie et al. (2011). "Mental models: an interdisciplinary synthesis of theory and methods." In: *Ecology and Society* 16.1.

Kolikant, Yifat Ben-David (2001). "Gardeners and Cinema Tickets: High School Students' Preconceptions of Concurrency." In: *Computer Science Education* 11.3, pp. 221–245.

Levy, Sharona T. and Mioduser, David (2008). "Does it 'want' or 'was it programmed to...'? Kindergarten children's explanations of an autonomous robot's adaptive functioning." In: *International Journal of Technology and Design Education* 18.4, pp. 337–359.

Malt, Barbara C. and Sloman, Steven A. (2007). "Artifact categorization: The good, the bad, and the ugly." In: *Creations of the mind: Theories of artifacts and their representation*. Oxford, UK: Oxford University Press, pp. 85–123.

Mawby, Ronald et al. (1984). *Structured Interviews on Children's Conceptions of Computers*. Tech. rep. 9. Bank Street College of Education.

Mortimer, Eduardo F. (1995). "Conceptual Change or Conceptual Profile Change?" In: *Science & Education* 4.3, pp. 267–285.

Mumtaz, Shazia (2002). “Children’s Conceptions of Information and Communications Technology.” In: *Education and Information Technologies* 7.2, pp. 155–168.

Oleson, Kristin E. et al. (2010). “Developmental Human Factors: Children’s Mental Models of Computers.” In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Vol. 54. 19. SAGE Publications, pp. 1450–1453.

Papastergiou, Marina (2005). “Students’ Mental Models of the Internet and Their Didactical Exploitation in Informatics Education.” In: *Education and Information Technologies* 10.4, pp. 341–360.

Pea, Roy D. (1986). “Language-independent conceptual ‘bugs’ in novice programming.” In: *Journal of Educational Computing Research* 2.1, pp. 25–36.

Proudfoot, Diane (2011). “Anthropomorphism and AI: Turing’s much misunderstood imitation game.” In: *Artificial Intelligence* 175.5-6, pp. 950–957.

Sanders, Ian, Galpin, Vashti, and Götschi, Tina (2006). “Mental Models of Recursion Revisited.” In: *SIGCSE Bull.* 38.3, pp. 138–142.

Scaife, Michael and van Duuren, Mike (1995). “Do Computers have brains? What Children believe about intelligent artifacts.” In: *British Journal of Developmental Psychology* 13.4, pp. 367–377.

Simon, Beth et al. (2006). “Commonsense computing: what students know before we teach (episode 1: sorting).” In: *Proceedings of the second international workshop on Computing education research*. ACM, pp. 29–40.

Sorva, Juha (2013). “Notional machines and introductory programming education.” In: *ACM Transactions on Computing Education* 13.2.

Thuné, Michael and Eckerdal, Anna (2010). *Students’ Conceptions of Computer Programming*. Tech. rep. 2010-021. Uppsala University, Computational Science.

Tucker, Allen et al. (2003). *A Model Curriculum for K–12 Computer Science: Final Report of the ACM K–12 Task Force Curriculum Committee*. ACM. URL: `http://www.csta.acm.org/Curriculum/sub/CurrFiles/K-12ModelCurr2ndEd.pdf` (visited on Nov. 12, 2015).

Turkle, Sherry (2005). *The second self: computers and the human spirit*. 20th anniversary ed. Cambridge, MA: MIT Press.

van Duuren, Mike and Scaife, Michael (1995). “How Do Children Represent Intelligent Technology?” In: *European Journal of Psychology of Education* 10.3, pp. 289–301.

– (1996). “‘Because a robot’s brain hasn’t got a brain, it just controls itself’ – Children’s attributions of brain related behaviour to intelligent artifacts.” In: *European Journal of Psychology of Education* 11.4, pp. 365–376.

van Duuren, Mike, Dossett, Barbara, and Robinson, Dawn (1998). “Gauging Children’s Understanding of Artificially Intelligent Objects: A Presentation of ‘Counterfactuals’.” In: *International Journal of Behavioral Development* 22.4, pp. 871–889.

Weiskopf, Daniel Aaron (2009). “The plurality of concepts.” In: *Synthese* 169.1, pp. 145–173.

Wolfe, Lee R. (1968). “Computer concepts possessed by seventh-grade children.” In: *The Arithmetic Teacher* 15.1, pp. 35–39.