"Draw Us How Smartphones, Video Gaming Consoles, and Robotic Vacuum Cleaners Look Like from the Inside": Students' Conceptions of Computing System Architecture

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ABSTRACT

From a constructivistic perspective on learning, it is essential to build on learners' previous knowledge in learning scenarios. Since computing system hardware design and principles of computing system organization constitute key parts of computer science classes, the identification of respective pre-conceptions is one of the core areas of computer science education. According to cognitive science learning aspects, the knowledge of the individual parts of which such systems are composed plays a decisive role in understanding them. Thus, this paper presents a self-contained substudy of secondary school students' mental modelling of computing systems with special focus on what we conceptualize as part-whole-thinking. Sixty eight secondary school students were asked to draw their conceptions of what three exemplary computing systems (smartphones, video gaming consoles, and robotic vacuum cleaners) look like from the inside. A content analysis of the 204 drawings received was carried out from evaluative, quantitative, and qualitative points of view. From the mental models expressed by the students in their drawings, insights into common conceptions are derived. Looking ahead, recommendations can be implicated from the main results.

CCS CONCEPTS

• **Social and professional topics → Computer science education**.

KEYWORDS

learners' conceptions, mental models, educational reconstruction, part-whole-thinking, drawing task

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1 INTRODUCTION

Computing systems are encountered in more and more situations in everyday life. Even though these different systems – whether they are smartphones, video gaming consoles, or robotic vacuum cleaners – are continuously and dynamically evolving and changing, their basic technological principles and their fundamental architectures remain constant, static, and applicable to each other (cf. Sec. 2.3). Thus, as Robertson et al., for example, state very aptly, in *computer science education* (CSE) "it is just as important [as solving problems related to computational thinking] that learners are aware of machine architecture limitations and how it is very different from how human brains think" [39]. With computing systems forming a core concept in international curricula such as the "K-12 Computer Science Framework" [24], students in early *computer science* (CS) classes worldwide are increasingly expected to obtain basic knowledge on how which parts work together to form computing systems for example. Following a constructivistic understanding of learning (cf. Sec. 2.2), lessons should be based on students' existing, pre-instructional conceptions. Thus, research on typical, relevant learners' conceptions constitutes a core research area in the academic field of CSE.

To lay a groundwork for this particular (pre)conception-research, the research project superordinate to this contribution is commited to the investigation into learners' ability to think in parts and wholes (cf. Sec. 2.1). In an earlier concept mapping interview study [36], eight secondary school students were interviewed on their conceptions around the basic architectures of smartphones, video gaming consoles, and robotic vacuum cleaners exploratively already (cf. Sec. 2.4.4). The analysis of students' drawings of how they believe computing systems look like from the inside presented here completes the empirical part of the overall research project.

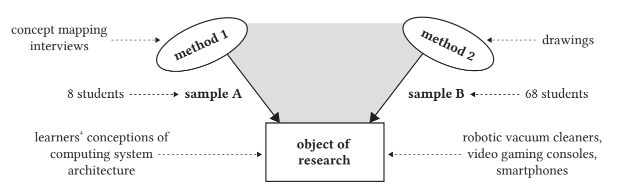

Figure 1: Between-method triangulation in this survey's overarching research project

This *between-method triangulation* [7] of two self-contained, qualitative methods that are applied to two different samples take on the same object of research (cf. Fig. 1). It is applied both to validate the results of the interview study and to draw further conclusions through additional insights by accessing a larger number of subjects and additional focus on evaluative and quantitative analyses (cf. Sec. 3.3). Thus, like the concept mapping interviews, this drawing study will also focus on learners' conceptions of the general structure of computing systems by using a *robotic vacuum cleaner* (RVC), *video gaming console* (VGC), and *smartphone* (SP) as exemplary systems. The overall research questions (RQ1-RQ5) of the research project are:

- RQ1: What conceptions do students have and develop of the (general) functioning and structure of computing systems (such as RVCs, VGCs, and SPs)?
- RQ2: Which parts do they identify and to which components do they attribute significant meaning?
- RQ3: What relationships of the components with each other do they identify?
- RQ4: What interrelationships do they bring different computing systems (wholes) into?
- RQ5: In which other computing systems (wholes) do the students rediscover the corresponding components (parts)?

For this particular drawing study, these research questions that are superordinate to the whole research project can be concretised for evaluative and quantitative purposes as presented in Sec. 3.3.

2 BACKGROUND

2.1 Part-Whole-Thinking

As we have pointed out in previous theoretical papers [35, 37] with reference to relevant literature from the field of cognitive science, a key component of human cognition is the identification of individual parts that make up a holistic system and their interrelationships to one another. Through this process it is subconsciously understood how objects, systems, and processes work. The acquired knowledge is then stored in mental organization hierarchies that reflect identified part-whole relationships. The knowledge of how the individual parts work is the basis for understanding (new) complex objects and systems. Especially computing systems are to be understood via elementary part-whole relationships (cf. Sec. 2.3).

Within the scope of the superordinate research project of this article, the corresponding thinking skill is conceptually termed by us as *part-whole-thinking* (PWT) and understood as the cognitive skill

- to identify (recognize and identify) individual parts of systems and objects (wholes),
- to understand their functionality independently of the whole,
- to understand the roles that the different parts of the system play in relation to each other and in relation to the whole,
- and to extrapolate the functioning of (new/other) systems in this manner.

Although developed independently, our definition is consistent with what Booth Sweeney and Sterman define as *systems thinking*: Their definition has been used as a theoretical basis in the field of technology education with regard to studies on understandings of *technological* systems (cf. Sec. 2.4.4), though Booth Sweeney and Sterman's initial ideas were rather about *social* systems.

2.2 Research on Learners' Preknowledge

2.2.1 Constructivism. As Vosniadou and Brewer stated in 1992, "research in cognitive science, science education, and developmental psychology during the last decade has shown that children [...] construct an intuitive understanding of the world which is based on their everyday experience" [45]. This epistemological view is the basis of *constructivistic* learning theories, that "developed by merging various cognitive approaches with a focus on viewing knowledge as being constructed" [13, 488]. Such construction mostly is based "on the grounds of the already existing knowledge" [10]. As Mertala points out refering to Vosniadou and Brewer, the synthesis of received information from others, adults, or everyday experiences forms coherent *mental models* (cf. Sec. 2.2.3) [32]. The accompanying learners' preinstructional *conceptions* (cf. Sec. 2.2.3) therefore need to be considered as "*points of departure* for guiding them to the science knowledge to be achieved" [10].

2.2.2 Educational Reconstruction. In the *Model of Educational Reconstruction* (MoER), which "is embedded within a constructivist epistemological framework" [10], this particular significance of learners' preknowledge is taken into account by putting the investigation into student perspectives in relation to the clarification and analysis of science subject matter and the design and evaluation of learning environments [12]. Diethelm et al. have adapted the model and extended the original form by aspects that are especially relevant for CSE [8]. With concrete focus on PWT (cf. Sec. 2.1), our research aims to tackle this investigation into learners' conceptions of computing systems in order to provide relevant research on learning in the sense of the MoER.

2.2.3 From Conceptions and/to Mental Models. While the majority of science education literature speaks of *conceptions* with reference to (investigations of) preknowledge (in the frame of educational reconstruction), "*mental models* have been a central issue in cognitive psychology" [16] conceptually at the same time. Some scientists even seem to be using both terms synonymously, especially in the context of the aforementioned research into relevant prior knowledge (cf. e.g. [29] or some of the literature mentioned in Sec. 2.4 and Tab. 1). However, Franco et al. characterise both *conceptions* and *mental models* as "*forms of representing the world*, that can be expressed through action, speech, writing, drawing or prototypes, such as objects in museums" [16]. Beyond that, though, they differ in detail:

Conceptions "express a *domain-specific* understanding of *particular* ideas and phenomena" [16] and "appear to constitute a relatively *static* description of a situation" [16]. *Mental models*, on the other hand, "refer to *dynamic* situations" [16] and "are global in that they involve inter-related elements" [16]. Refering to Craik and Johnson-Laird, Jones et al. note that "there is widespread agreement in the literature that mental models are 'working models' [...] and are therefore dynamic [representations]" [23]. Thus, mental models "are constructed by individuals based on their personal perceptions [...] and understandings of the world" [23]. This totally is in line with constructivistic works (cf. Sec. 2.2), in which *learning* might even generally be regarded as *mental modelling* [11]. Therefore, mental models represent reality incompletely mostly [23]. In particular, we follow the widely cited definition of Rouse and Morris and "consider a mental model in terms of its functionality and conceive it as a cognitive structure that enables a person to describe, explain, and predict a system's purpose, form, function, and state" [23].

So, does the term "conceptions" or "mental models" apply in a study like this, in which drawings are used to examine learners' prior knowledge of the structure of computing systems? To answer that question, first of all, it has to be reconsidered that neither conceptions nor mental models can be elicitated directly, since both "exist within the mind and are therefore not available for direct inspection or measurement" [23]. Only through external representation (as by drawing, for example, cf. Sec. 3.1), researchers "can speculate what the students' conceptions [...] or mental model(s) are in their minds" [29]. For us, therefore, the mere "drawings of their conceptions" (as the title hints at) are to be seen closer to the internalized mental models, which in turn are constructed on the basis of pre-existent conceptions (as mentioned above). This interrelationship, in combination with the existing "discrepancy [...] over where in the mind [(working memory or long-term memory)] mental models are hypothetically located" [23], leads to the point that a precise distinction between the two concepts is superfluous at this point. The goal of this drawing-study, however, remains the investigation into learners' pre-conceptions, which in our understanding are in turn represented in the mental models externalized via drawings.

2.3 Scientific View on the General Structure of Computing Systems

In order to discuss the learners' mental models with regard to their proximity to the actual structure of computing systems, it is essential at this point to scientifically describe the corresponding fundamentals. In the MoER (cf. Sec. 2.2) this step is specified as "the clarification and analysis of science subject matter" [12].

Every *computing system* is made up of a specific combination of *hardware*, *software* and *network connections* [3]. On the *hardware* side, every computing system embeds at least one digital computer (sometimes called microcontroller [44]), which "consists of an interconnected system of processors, memories, and *input/output* [(I/O)] devices" [44]. As Robertson et al. point out, "the main components in a modern computer and the way in which they are interconnected are still based on the von Neumann architecture from 1945" [39]. Originally, this architecture consisted of "the memory, the arithmetic logic unit, the control unit, and the input and output equipment" [44]; Tanenbaum and Austin refer to the arithmetic logic unit and the control unit, which "are combined onto a single chip called the CPU (Central Processing Unit) [in modern computers]" [44], as the computer's "brain". Usually, "CPU, memory, various I/O devices (such as a sound chip and possibly a modem), as well as interfaces to the keyboard, mouse, disk, network, etc., and some expansion slots" [19] are placed on one single printed circuit board in modern personal computers. Variable *software* programs and data, which may either be stored on internal or external storage units, are transmitted through I/O units to the random access memory (RAM) in machine language; programs that are automatically executed at start-up (such as the basic I/O system, i.e. BIOS) are stored in the EEPROM (flash electrically erasable programmable read only memory) [15]. *Network interfaces* allow multiple computing systems to connect and communicate with each other.

Thus, the bottom line is that every computing system is based on the principles of the IPO model [15]. Apart from that, various computing systems like robotic vacuum cleaners, video gaming consoles, and smartphones mainly differ in their I/O devices.

2.4 Related Work

While some current studies investigated which *taxonomies* learners of computing systems mentally create already [4, 42], we are not yet aware of any work from the field of CSE that *specifically focuses* on *partonomic thought structures*. However, in recent years there have been numerous publications in which learners' conceptions of how computing systems such as computers [20, 21, 32, 39, 41], smartphones [3], or robots [30, 33] work have been examined. These publications were reviewed for indications of learners' conceptions of the *structure* and *configuration* of the various computing systems. The resulting summary is given below.

2.4.1 Computers. Robertson et al. interviewed primary school students on their conceptions of how computers work. With regard to a computer's components, "the most common answers mentioned batteries and wires" [39], which "'helps the computer work'" [39]. Thirty years earlier, these particular themes (wires, electricity, and plugs) were already noted by Hughes et al., who interviewed children about their models of computers [20]. In addition, older children commonly also bring up plugs, switches, buttons, levers, hard drives, discs, and chips [39] nowadays. In this regard, Jervis reports that children represent "wires and plugs as entities in themselves, that is not as mere connectors for the various components [...], but as important and significant parts of the computer" [21]. As Rücker and Pinkwart assume in their review and discussion of children's conceptions of computers, "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" [41]: "What exactly is wired to what, however, initially remains a complete mystery, a tangle" [41]. In Mertalas drawing study with 65 students, "only two drawings contained information about how computers might look inside" [32], which implies the need for specific focus on drawing the inside for the tasks in this study (cf. Sec. 3). Anyhow, in "both drawings, the child had drawn a square shape with wires inside" [32].

2.4.2 Smartphones. In one of the very few studies on learners' conceptions of how smartphones work, Brinda and Braun found out that half of the interviewed students "imagined that data is saved externally, for example on an external server or a cloud up in the sky" [3]. One learner even thought "that data needs no space, since it consists of bits and bytes and as such has no physical presence" [3]. They also noted that learners typically consider "smartphones to be generally inferior to other computing systems, since smartphones cannot connect to as many external devices" [3]: Students named "smaller memory, slower processing units and weaker video cards" [3]. This seems remarkable considering the recent advantages in smartphone technology and the performance of many smartphones reaching the level of desktop computers nowadays.

Year	Author(s)	Research object	Sample (age range)	Ref.
1990	Gray	mental model construction during hypertext navigation	adults	[17]
1993	Denham	children's conceptions of computers	9- to 14-year-old children	[6]
2003	Jervis	mental models of computers	7- to 11-year-old children	[21]
2003	Sheehan	perception of people programming computers	6-,7-,9-, and 10-year-old children	[43]
2005	Papastergiou	mental models of the Internet	12- to 16-year-old students	[38]
2011	Dinet and Kitajima	mental models of the Web	10- to 14-year-old children	[9]
2017	Kodama et al.	mental models of Google	10- to 14-year-old students	[26]
2018	Brauner et al.	mental models (in the sense of stereotypes) of computer scientists	10- to 13-year-old students	[2]
2019	Mertala	children's conceptions of computers, code, and the Internet	young children aged 5 to 7 years	[32]
2019	Waldvogel	learners' conceptions of how the Internet works	students (age unknown)	[46]

Table 1: Overview on exemplary literature from the field of CS(E) presenting research that is using drawing tasks

2.4.3 Robots. Müller and Schulte "analyzed 79 questionnaires [...] of children between 7 and 10 years" [33] to investigate their conceptions of robots. They conclude, that children commonly consider robots to be controllable, either through some sort of remote-control or through programming and computer programs [33]. Furthermore their results show, that robotic vacuum cleaners are among the most well-known robots[1]. In their investigation of young children's perspectives in explaining a self-regulating mobile robot, Levy and Mioduser found out, that instead of describing it technologically "children turn to the simpler structure (and language and terms) of a psychological description" [30], when its behaviors and tasks "require grasping a greater number of interacting components" [30]. They attribute this to the fact that "technological descriptions are more detailed, complex, specific and locally attached to particular components of the system" [30].

2.4.4 Previous Studies on PWT. The conceptions just summarised have been largely repeated by eight 13- to 14-year-old secondary school students in our preceding concept mapping interview survey [36]: In our prototypically summarised mental model of the structure and configuration of the computing systems in question, a central component, which the students referred to as a drive, hard disk, or "chip(s)" in the interviews, combines tasks of (data) processing, data storage and, in some cases, even power supply, and also serves as a place for the programming. Special importance is also ascribed to ports (e.g. for power cables, input devices such as controllers, or external output devices such as televisions). In the prototypical mental model, individual components are wired.

Although we are not aware of any other studies from the field of CSE that specifically focus on aspects of students' preconceptions about PWT or related aspects, there are some studies – mainly from the field of technology education – that pursue similar questions regarding the approaching and understanding of technological systems. In an interview study, Koski and de Vries for example asked primary pupils what a coffee maker and a washing machine need to make coffee or do laundry, in order to develop an understanding of their intuitive *systems thinking* (cf. Sec. 2.1). The students of their investigation "often address[ed] the system[s] at hand from a linear point of view with the emphasis on experience gained by using it" [27]. Though they were able to identify different parts that refer to the concepts of input (like water, electricity, buttons) and output (like coffee, warm water, or wet clothes), they did not indicate, how specific parts work together. By building their explanations on their experience in using the systems, they "were not able to explain relations connecting inputs, processes and outputs" [27]. Hallström and Klasander came to similar conclusions when they examined technology student teachers' conceptions of mobile phones, elevators, and the electric grid system. Most of their students "could see the various parts [of these systems] but were unable to connect them to a wider context" [18]. In addition to that, "the parts of the systems that the students understood were mostly the visible parts, either components, devices, or products such as buttons, power lines, hydroelectric plants, or the interface with the software inside a mobile phone" [18]. More difficult to understand were "the 'invisible' or abstract aspects of the technological systems, such as flows of information, energy or matter, or control operations" [18].

[1]Initially, this was corresponsible for us to include robotic vacuum cleaners representative of robotic systems in this study's set of computing systems.

3 METHOD

3.1 Methodology

In our culture, language and written text as means of expression have long prevailed over non-linguistic expressions. Drawings and paintings were addressed to illiterate recipients, which led to a long period of time in epistemology and education theory not attaching them any value [34]. Nevertheless, various drawing methods have also found its way into research in CS(E) in recent decades, as the exemplary overview of corresponding publications in Tab. 1 shows. One of the older works listed there is by the computer scientist Denham, who presents and discusses the method in detail, referring in particular to research on mental models of computers [6]. He notes that an approach with drawings offers an advantage over a survey with interviews, particularly with regard to two points: First, on account of *the young age of the subjects* and their scholastic imprint, they might perceive interviews as a form of assessment or test, leading to a threatening situation. This, together with limited powers of verbal expression, potentially results "in withheld or modified responses [...] and [...] a reluctance to say anything that might appear 'silly' or 'wrong'" [6]. Second, the *nature of the mental models* about which information is sought, requires the promotion of thinking through a non-linear problem. However, "unlike sequential tasks, such as solving an arithmetic problem, the interview situation does not lend itself well to [this]" [6].

Denham considers drawing to be an alternative, promising method of expression that, because it is 'safe' and 'enjoyable', "allows the subject to transcend the barriers of language, self-consciousness about existing knowledge and understanding" [6]. Especially complex tasks like expressing knowledge of the general structure of computing systems become more manageable when novices are asked to draw these [6]. Thus, unsurprisingly, drawings are recently becoming a popular research tool to "establish a non-confrontational basis for interactions, where children can draw and are not forced to maintain eye contact with researchers" [14]. In the course of this, "much of the attention to children's drawings has been on the finished product and the labelling of that product" [14]. Nevertheless, in some studies (cf. also the works in Tab. 1) the drawings are accompanied by interviews. This of course reduces difficulties in gaining insight into children's understandings and perspectives [14], but at the same time significantly increases research effort.

One way of retaining to the intended, larger number of subjects (cf. Sec. 1) and avoiding interviews is to specifically ask the students to label their drawings at data collection: Since "words anchor meanings, [...] once a label is attached to a drawing, the meaning is ascribed" [14]. In addition, the participants should also be explicitly given the opportunity to add short, textual descriptions to their drawings. These needs were taken into account in the drawing assignments that were developed for this survey (cf. Appendix A) and evaluated in a pilot study with three students (1 girl, 2 boys, 6th grade, 11.3 years old on average). The pilot data collection was completed after shortly less than 20 minutes. The response time was considered adequate, taken into account with regard to the planning of the data collection, and communicated to all involved.

3.2 Sample, Data Collection, Data Preparation

The data used for evaluation consists of 204 drawings[2] produced by 68 ten- to twenty-year-old students (three drawings each) from five different German secondary schools in 2019. Table 2 presents information on participants' grade levels, the mean age for the participants of each of these levels, and the gender distribution. Through the contact with the supervising teachers it can be assumed that the eleventh and twelfth graders already had CS classes[3]. According to the respective teachers' reports, the remaining students (grade levels 5 to 10) had no previous classroom experience in CS.

The exercise was either carried out at the beginning of the students' participation in various workshops offered by the authors' research group at university[4] or in preparation of these at school. The drawings were scanned, the digital image files were cropped, and their contrast has been increased. Monochrome drawings were converted to grayscale image files to save storage space.

Despite the broad age range, the sample is treated as one single group in the analysis (Sec. 3.3). On the one hand, this is due to the fact that, despite the age difference, the results of the related

[2]Inluding five drawings that were left blank (cf. Tab. 3) and nine drawings from the pilot study (cf. Sec. 3.1)

[3]Programming with Java using the Greenfoot environment and Arduino microcontroller programming have already been addressed in prior classes in these groups for example according to one of their teachers.

[4]These workshops were mostly addressing girls, which explains the relatively high proportion of female participants in this survey.

grade level	**mean age**	**female**	**male**	**not specified**	**sum**
5th	10.8 yrs.	5	0	0	5 (7%)
6th	13.1 yrs.	5	2	0	7 (10%)
7th	12.5 yrs.	13	0	0	13 (19%)
8th	13.6 yrs.	5	0	0	5 (7%)
9th	15.2 yrs.	8	0	0	8 (12%)
10th	16.0 yrs.	11	0	0	11 (16%)
11th	15.2 yrs.	6	3	1	10 (15%)
12th	18.0 yrs.	3	5	0	8 (12%)
not spec.	17.0 yrs.	0	1	0	1 (2%)
mean/ sum	14.5 yrs.	56 (82%)	11 (16%)	1 (2%)	68 (100%)

Table 2: Overview on participating students

work do not differ significantly from our results from the interviews (Sec. 2.4.4). After a first review of the material, with regard to the RQs, no relevant age differences could be detected regarding the structures drawn either. Thus, the additional effort resulting from splitting up the sample did not seem appropriate for this analysis.

3.3 Analysis

The entire computer-aided data evaluation is carried out according to the basic principles of Mayring's *content analysis* [31], with different approaches (evaluative, quantitative, qualitative) being applied in the individual cases.

3.3.1 Evaluative Analysis. In the first step of data analysis, each drawing was assigned to exactly one of six deductively generated *evaluative categories*[5]:

one-centered: the drawn computing system has *one central component* that is connected to all or most of the other components

several-centered: the drawn computing system has *several central components* that are connected to all or most of the other components and to each other

spaghetti: the components of the drawn computing system are so tangled up in the drawing that it resembles a plate of *spaghetti*

unconnected: the drawn system contains several, but *unconnected*, components

not evaluable: the drawing cannot be evaluated with regard to the (evaluative) research questions, for example because it pursues exclusively an artistic aspect and thus misses the task

left blank: the task was not processed, the corresponding page in the questionnaire was left blank

For this *evaluative* part of the *content analysis*, a co-rater (master's degree in CSE) was consulted, who was provided with the coding agenda (including coding examples) and independently categorized a randomly[6] chosen set of 60 drawings in order to evaluate the coding agenda. The *inter-rater reliability* was tested for the

[5]Coding examples of these evaluative categories are given in Fig. 2.

[6]Constraint: 20 drawings per computing system that are different from the provided coding examples

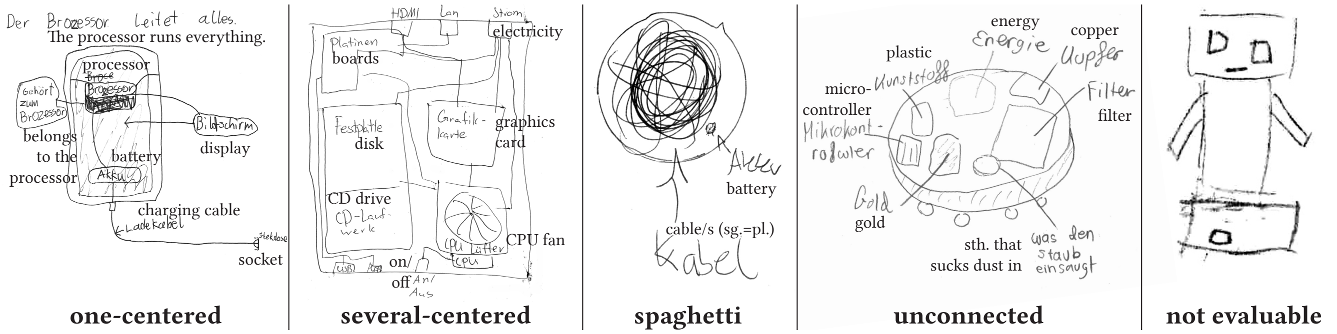

Figure 2: Coding examples for the evaluative categories (translated from German into English where appropiate)

evaluative items and a *Cohen's kappa coefficient* of $\kappa = 0.815$ was measured, which is considered as an "almost perfect" [28] agreement. For the sake of simplicity, only the values for the main rater (first author) were considered for further evaluation and are given in the following, as there were only insignificant differences between both raters for evaluation purposes.

The assignment of the drawings to these evaluative categories allows the following RQ to be answered:

RQ1.1: Which distribution of the conceptions of the structure of computing systems (one-centered, several-centered, ...) results for the investigated sample?

3.3.2 Quantitative Analysis. Certain questions related to this research design can also be approached quantitatively[7]:

RQ2.1: Which components do the students label most frequently?
RQ2.2: For the "one-centered" drawn computing systems, which are the most commonly presented central components?
RQ5.1: Which of the components do students most often rediscover within the three computing systems to be drawn?

This procedure corresponds in its main features to a *quantitative content/frequency analysis* [31], where the counts are realized by coding into inductively developed, summarizing categories.

3.3.3 Qualitative Analysis. This part of the evaluation involves the greatest risk of third party misunderstanding. Therefore, the statements made in the qualitative evaluation of the drawings should certainly be treated with great caution. However, they can be used both for validation of the findings from the preceding interview study (cf. Sec. 2.4.4) and for further knowledge acquisition through triangulation (cf. Sec. 1). Thus, in the last but most complex step of the analysis, the material is reviewed according to the procedures of a *qualitative content analysis* with *inductive* category formation [31]. In this process, the material is evaluated under the same RQs as of the superordinate research project (cf. Sec. 1) to allow triangulation.

4 RESULTS

4.1 Results of the Evaluative Analysis

4.1.1 Distribution (→RQ1.1). The evaluative analysis has shown that in the majority of the drawings (39%) the students did not (or did not know how to) connect the individual components within the computing systems (*unconnected*). It is also worth mentioning in the context of the evaluative evaluation here that the number of drawings presenting computing systems as *one-centered* is almost identical to the number of *several-centered* ones (cf. Tab. 3).

evaluative category	codings SP	VGC	RVC	sum
one-centered	11	17	11	39 (21%)
several-centered	16	10	9	35 (16%)
spaghetti	2	5	4	11 (6%)
unconnected	32	20	27	79 (39%)
not evaluable	7	15	13	35 (16%)
left blank	0	1	4	5 (2%)
	68	68	68	204 (100%)

Table 3: Overview on the evaluative codings

When looking at the distribution, it is further noticeable that the proportion of non-evaluated drawings (evaluated as *not evaluable* or *left blank*) was significantly higher for the VGC (24%) and the RVC (25%) than for the SP (10%). This may either be due to the fact that this corresponds to the sequence of questions in the questionnaire (cf. Appendix A) or it may be a first indication that learners are more likely to (be able to) express their conceptions about the structure of computing systems through systems they are more familiar with.

4.2 Results of the Quantitative Analysis

4.2.1 Labeled Components (→RQ2.1). The quantitative analysis of the labeled[8] parts in the 204 drawings resulted in a total of 794 codings. Seven hundred and fifty two of these refer to "component-object" (like "battery", "button", etc.) and 42 to "stuff-object" (like "copper", "gold", etc.) relations, which are the two main types of part-whole relationships [47].

The most frequently labeled *components* across all 204 drawings are "batteries" (99x), "buttons" (61x), "sensors" (54x), "cables" (53x)

[7] A limiting factor in this respect is that only labeled components must be counted in order to avoid misinterpretations.

[8] Labels listed in this Sec. 4.2 were translated from German into English and terminologically summarized where appropriate (cf. Sec. 3.3.2). If a drawing contains several components that can be summarized to one category (e.g. several switches such as "home button", "on/off switch", or "volume switch"), this drawing was assigned to the corresponding summarizing category (e.g. "button") only once. The summarizing category is named after the most frequently used term contained in it, if no taxonomic generic term can be formed from the answers (such as "button" from "on/off button" and "volume button").

and "connectors" (45x). After "mechanical components (RVC)" (44x) associated with RVCs, "(micro-)controllers" (39x) come seventh in the ranking and "memory components" (36x) eighth. Other noteworthy components such as "processors" (21x), "software" (11x), or "Wifi" (8x) and "Internet" components (4x) follow further below in the ranking. Regarding the *materials* of which the computing systems are made from the students' conceptions, it can be observed that they were labeled with "copper" (11x), "gold" (9x), "metal" (6x), "aluminium" (6x), "plastic" (6x), "zinc" (3x), and "(plexi)glass" (1x).

4.2.2 Centers of one-centered drawings (→RQ2.2). For the 39 one-centered-evaluated drawings (cf. Sec. 4.1), most of the students labeled the center as *"battery"* (7x), closely followed by *"processor"* (6x). Following are a summary/combination of different terms ("computer", "computer board", "computer chip") related to *"computer"* (5x). The same number of drawings contain *"microcontrollers"* (4x) as the center as an *unlabeled* (4x) component. In fewer drawings, a *"memory card"* (3x) and *"mother/circuit board"* (2x) were tagged. In one drawing each, the central component was labeled as *"plug"* (1x), *"control center"* (1x), *"memory"* (1x), or *"motor with battery charging"* (1x) or the central role was assigned to the *"CD drive"* (1x), a *"sensor"* (1x), the SP's *"touchscreen"* (1x), or the RVC's *"absorber"* (1x).

4.2.3 Rediscovered components (→RQ5.1). Between all three systems (SP, VGC, and RVC), components were rediscovered 52 times. In this context, more components were rediscovered just between the SP and the VGC (113x) than between the VGC and the RVC (78x) and the SP and the RVC (80x). However, only 30 students (44%) have rediscovered at least one component in all three systems.

The components that students rediscovered (i.e. labeled) most often across all three systemswere "batteries" (14x), "(micro-)controllers" (9x)[9], "buttons" (6x), "connectors" (4x), and "processors" (4x).

4.3 Results of the Qualitative Analysis

In qualitative research on conceptions, it is both common and appropriate to present special, exceptional, and individual as well as typical cases as part of the presentation of results. Corresponding, typical conceptions could then be used to constructively address them in CS lessons (cf. Sec. 2.2 and 5). Thus, expressive examples[10] of conceptions, which were identified in the course of the qualitative evaluation, are presented below following the inductively developed category system (cf. Sec. 3.3.3).

4.3.1 Parts (→RQ1, →RQ2). Regarding the ability of the RVC to orientate itself in its area, two students (N01 and H12) assign a GPS module to it. This component also "prevents it from driving through the same room 10 times by remembering where it's been" (N01). In individual cases, the manoeuvring of the RVC is also described to function camera- or ultrasonic-based (e.g. N06). Some students describe the possibility of connecting the RVC to the SP (e.g. N04) and "telling it where to drive" (H11), which indicates the conception of a manually preset routing. However, the majority of students attributes this more generally to its *sensors* (e.g. N08). Three students (P01, P02, and Q01) describe that the robot drives straight ahead "until the pressure sensors detect something and it turns around or until the battery level drops and he returns to the charging station" (P02). One of them compares sensors to (pressable) buttons (Q01). In the same manner, the functionality of touch screens (for SPs and VGCs for example) is also assigned to pressure sensors (e.g. P01). Some drawings also allow conclusions to be drawn about the conception of a "fine network of electrically conductive material behind the display that transmits a signal to the computer in the mobile phone when touched" (N07). Or, more generally, sensors behind the display are considered responsible for it to function (e.g. H04). Similarly, sensors are made responsible for "sensing the movements of the controller" (N04) – i.e. receiving input commands from the (wirelessly) connected controller (e.g. N01) – and "transmitting them to the 'little brain'" (N04). One student even calls the control buttons on controllers of VGCs "pressure sensors" and joysticks generally "sensors" (P02). When such buttons are pressed, corresponding data is collected and forwarded (to the VGC's screen in this particular case) according to the conception of another student (N07). Accordingly, one student labels a part connected to the processor with "data for vacuuming" (P02) in the RVC. Analogously, a further student describes that sensors provide "information" (H09). Some students describe similar phenomena in terms of "signals" that are forwarded (e.g. P02), while others merely describe "control" through a central component (e.g. N01).

The processing of data takes place either in a *computer* (e.g. N07[11]), a *mini computer* (e.g. H25), or a *computer chip* (e.g. H09, cf. Fig. 3) in the respective computing system. One student attributes the task of "calculation/processing" (H06) to a *CPU*, others attribute the control of the other components to a *processor* (e.g. P03) or a computer (e.g. Q02). In one particular case, a student assumes that "a *motor*, which is always charged through a charging cable, drives the lamps ['in XXXXS'] of the [smart]phone" (N04).

Individual drawings describe how something is stored on these various central components, which was summarized under "software" in the quantitative analysis (cf. Sec. 4.2): For example, one student describes that "the *codes* are stored on the microchips in the RVC" (H02), whereas she describes more specifically that the microchips in SPs contain "stored *software*" and the "*operating system*" (H02). Thereby the task of the operating system in the example of the RVC is the "execution of the different mechanisms [by cable]" (H02). To some extent - especially in the group of eleventh graders[9] - students also differentiate between "programming" and "software": While the programming lies on the microcontroller (e.g. H04 and H28) in SPs, "stored data" (H28) is assigned to the SD card in the SP, or software to a "data memory" (H28) or to the motherboard (e.g. Q01) in the VGC. At this point, therefore, further research should be consulted on the extent to which students conceptually distinguish between codes, programming, software, data, and information. In this context, the representation of "software" in the students' minds also seems to be meaningful, as one student for example describes that the "information/programming on the cartridge with the game on it is *mirrored* on the [VGC's] screen" (N02). Other students describe that the screen connected

[9] All students who have labeled "(micro-)controllers" in all three computing systems belong to the group of eleventh and twelfth graders, for whom it cannot be excluded that the workshop in which the data collection took place was promoted as microcontroller programming by the supervising teacher.

[10] Given examples were translated from German into English where appropiate. A three-character long key is used for reference to the raw drawings (cf. Appendix A).

[11] It is noticeable that N07 draws a computer inside the SP and the VGC, but attributes "data processing" to a "circuit board" in the RVC, where she labels no computer.

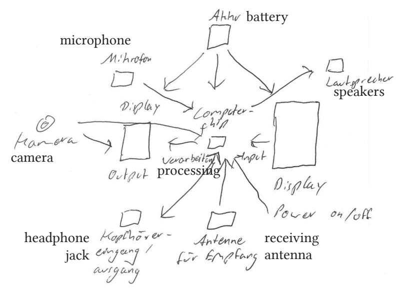

Figure 3: Representation of a computer chip as the central component and indications of an IPO-generalisation in H09's drawing of the SP.

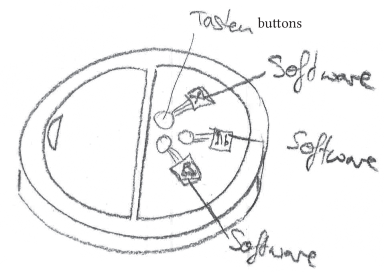

Figure 4: Representation of software attached to different buttons of the RVC distributively in Q01's drawing.

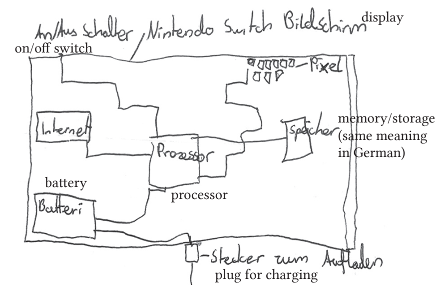

Figure 5: Representation of the Internet as a component within a VGC in P02's drawing.

to a VGC "displays the data in pictures" (H28) or that "the CD is converted into pictures" (D04).

With regard to the second most frequently labeled component, *buttons*, most students rather describe *what* they are used for (e.g. to switch the device on and off, to control the volume, or to access the main menu) than *how* they contribute to the whole. Here, more exclusive appears a drawing in that software is attached directly to different buttons in a distributive manner (Q01, cf. Fig. 4). In a similar way, another student suggests that "for each button on the [VGC's] remote control there is a receiver[12] that processes and transmits its respective information" (N01).

The most frequently labeled component, the *battery*, acts as the "energy-" (N04, H07, H13) and "power-supplier" (H06, H09), powers "all things" (N04), constitutes the "basic energy supply system" (N03), is particularly "large because a lot of energy is needed" (N07), and is designed to "turn the phone on and to keep it on" (O12).

4.3.2 Connections (→RQ1, →RQ3). The fourth most frequently labeled component are cables, which in most of the drawings "connect everything together" (Q02). In terms of linking the individual components, a closer look at the drawings reveals that the students often link components (inputs) *directly* to those they affect (outputs): For example, volume buttons are connected directly to the SP's speaker (N01 even describes this in writing), the camera is linked directly to the smartphone's display (H09) or (in the case of the conception of camera-based control) to the wheels of the RVC (H21), or the SP's battery is connected directly to its charging port (H28) as well as its on/off-switch (D02). Surprisingly, these examples are not limited to drawings that have been evaluated as several-centered, but cover almost all of the evaluative categories.

One of the few students who comment on the contribution of the cables writes that they "allow the other signals to work *better*" (N08). In this regard, single drawings and the descriptions contained within give reason to assume the idea of the components within computing systems communicating *over the air* with each other: This may be compounded by some students' uncertainty as to how the screen of foldable mobile VGCs could be connected to the other components (for example, "somehow", H21). A further indication of this could be the majority of the drawings in that the computing systems were drawn unconnected (cf. Sec. 4.1). However, the majority of the students describe cables as "forwarding and activating the signal" (D02) or "forwarding information" (H12). Some students recognize that the term "cable" may not be very appropriate and look for a "substitute" (D09): Examples are "connectors" (D09), "power plant" (H03), "short wires" (H16), or "copper colored strands" (N03). Only few describe that the components are "connected through circuit boards" (H06).

4.3.3 Wholes (→RQ4). One student's SP and VGC drawings show *the Internet* as an integral component within the two systems (cf. Fig. 5). Corresponding misconceptions are occasionally also found in other studies [32, 38]. However, the majority of students recognize that the Internet is an independent system (*whole*), which the three systems to be drawn (*parts*) can interact with via components such as "Wifi modules" or "antennas" (cf. Sec. 4.2). Accordingly, an interaction with *servers* can be seen in several drawings (e.g. D03, D04, D07).

Contrary to the idea of being build of computers, computer chips, etc. as *parts* (as discussed in Sec. 4.3.1), some students seem to assume that *computers* are composite "embedded" systems (autonomous *wholes*) within the three systems to be drawn that are practically interchangeable and that the SP, VGC, or RVC interacts with (e.g. H25, N07).

Self-contained components ("microcontroller", "Wifi unit", "battery", H05) are drawn and connected to each other within a VGC's *gaming controller* in one drawing. This creates the impression that the respective student understands it as an autonomously functioning computing system of the same basic structure that interacts with others. In combination with the VGC, *monitors* (e.g. D04) or *televisions* (e.g. N07) often appear as further wholes in addition to the before mentioned controllers; the directions of arrows drawn indicate an *generalization* (cf. Sec. 4.3.4) of these systems in the sense of the IPO model in certain cases (e.g. H07).

4.3.4 Generalizations (→RQ1, →RQ5). One twelfth grader[9] *generalizes* one of the computing systems to be drawn and describes that "a SP *is a microcontroller* where processors are included" (H11). Another one describes the graphics processing unit ("GPU") of a VGC as a "CPU in large & strong" (H06) and generalizes the display of the SP as the "user/device interface" (H06).

[12]This student exclusively uses the term "receiver", but describes the function of a transmitter in this context.

The qualitative analysis of the role of individual parts and wholes (cf. Sec. 4.3.1 and 4.3.3) has already suggested that input components and devices such as buttons and controllers could be generalized as sensors in the – especially younger – students' imagination. The scientific view, however, is that a generalization the other way around (sensors as input components) would be more appropriate (cf. Sec. 2.3). But also in correspondence with the IPO model, single components (e.g. P03, H09, cf. Fig. 3) or wholes (e.g. H07) seem to be generalised as input, processing and output in isolated drawings, with arrow directions representing the way of processing.

The frequencies of corresponding descriptions in the students' drawings suggest that computing systems are generalized by them as systems that *get warm* and thus *need to be cooled* (e.g. O01, H09) and in which there is "*electricity* all around" (e.g. H18 →*I4* cf. Sec. 5).

4.3.5 Materials (→RQ2) and learners' thoughts on sustainability (→excursus). In addition to the initial research questions, when analyzing the drawings, it was noticeable that several students described that the materials of which computing systems are built are "valuable" (N02) and "mostly difficult to cultivate and mine" (H19). For instance, according to one student, SPs are made of "ca. 0.1% gold" (H19). According to another respondent, one of the most expensive components is the battery in this respect (H11). These descriptions give reason to believe that students at the age of the respondents are currently sensitive to questions of the sustainability of systems and how their financial value comes about (→*I3*).

5 SUMMARY AND CONCLUSION

To summarize, most of the students did not connect the drawn components or did not know how to connect them (cf. Sec. 4.1). Besides, practically the same number of students thought that the components were connected in a net-like manner (*several-centered*) or mainly via a central component (*one-centered*)[13]. In this context, the amount of evaluable drawings indicates that they tend to have a more general idea (whether or not this is in line with the scientific view) of the structure of SPs than of RVCs and VGCs (→*I2*).

The most frequently labeled parts (cf. Sec. 4.2) in the drawings are those the students interact with directly while using the systems and which are therefore physically visible (e.g. buttons, displays, microphones, cameras, loudspeakers, ...) or whose internal presence they sense presumably because of personally experienced system or capacity limitations (e.g. battery, memory, ...).

Also from the results of the qualitative analysis (cf. Sec. 4.3) it can be concluded that the majority of students have purpose- and user-oriented conceptions of computing systems rather than that their mental models contain concrete and mature ideas of their structure, composition, and operating principles. Also the recognizable generalization of computing systems and their individual components in terms of the IPO model remains at an extremely rudimentary level or seems to be at best subconscious to many students. Nevertheless, this latter incomplete pre-knowledge is also an opportunity from constructivistic points of view (see below).

Basically, the results of this drawing study could thus substantiate and validate the initial findings from the exploratory concept mapping interviews [36] and extend them just like it was possible to extend the previous results from related work on conceptions of computing systems (cf. Sec. 2.4) with further aspects regarding conceptions of their (general) structure. This study thus joins the set of works on students' conceptions and adds to the still expandable knowledge of learners' pre-knowledge on CS topics.

However, results from research into conceptions must not be generalized and absolute statements should be avoided. Accordingly, the limitations of the results presented in this article regarding sample (size), possible misinterpretations in the analyses, and impossible generalizations must be considered throughout. Still, teachers have to be aware of the students' conceptions presented in this paper when they are teaching about the structure of computing systems and in preparation of these classes. Thus, in the following, four possible, examplary implications (I1-I4) will be briefly derived from a selection of the results of this investigation:

- I1: The most obvious implication is: cover the basic structure of computing systems in your CS classes. Ideally, let your students *disassemble* discarded computing systems.
- I2: To explain the structure of computing systems, do not only choose obvious examples (e.g. PCs), but *decontextualise* the knowledge using examples of further systems in which the students do not suspect similar basic structures, but which they encounter in their everyday lives (e.g. SP, VGC, RVC, etc.). Highlight the fact that all these computing systems are based on the same fundamental structures (cf. Sec. 2.3) and thus contribute to a demysthification of CS by this.
- I3: In your CS lessons, also address questions about the sustainability of computing systems, the materials of which they are built, and the circumstances of how these are mined. From the results of this research it can eventually be concluded that students develop an awareness of and interest in such issues today.
- I4: Admittedly, after this study the question remains open as to what students understand by "data" or "information" and how they relate them to "electricity": However, students are obviously aware that such systems "operate on electricity" and "process data". Thus, in your CS classes, show the connections that take place when representing information in the form of binary coded data (through input devices and components like sensors) and the electrical data transfer between individual components. Understanding the basic principle of digitizability is a crucial lever for understanding the functioning principles of computing systems. It enables students to understand the contribution of individual components by assigning them to the IPO model in the sense of PWT (cf. Sec. 2.1).

The results have shown that students – presumably through day-to-day contact – form conceptions of how computing systems work and how they are structured. These conceptions partly conflict with the valid scientific principles massively. Thus, it cannot be assumed that they acquire this basic knowledge simply by using these devices (→*I1*). However, in our experience CS lessons often still focus strongly on programming skills. They should *at least* include *basic* knowledge about the systems that continuously surround our students. After all, schoolbooks hardly address general computing system architecture also. Since teachers should be able to use teaching materials for their lessons that optimally take into account learners' conceptions from a constructivist perspective, the

[13] The latter corresponds more accurately to the actual structure of computing systems in the sense of the von Neumann architecture (cf. Sec. 2.3).

next step is to produce practioner guidances like Robertson et al. are also calling for on the basis of research into learners' conceptions for example [39]. From a methodological point of view, *concept cartoons* that "were developed in a search for strategies which could help to clarify the relationship between constructivistic models of learning, scientific epistemology and classroom practice" [25] are only one promising option here.

A SUPPLEMENTARY MATERIAL

Drawing tasks, scans of the raw drawings, and biographical info on the sample (anonymized) are linked under this publication's *Researchgate* page (https://doi.org/10.13140/RG.2.2.26281.21608).

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