Digital Experiences in Mathematics Education (2023) 9:420–443
https://doi.org/10.1007/s40751-023-00126-5

Spreadsheets in Secondary School Statistics Education: Using Authentic Data for Computational Thinking

Sylvia Patricia van Borkulo[1] · Christos Chytas[1,2] · Paul Drijvers[1] · Erik Barendsen[3] · Jos Tolboom[4]

Accepted: 24 February 2023 / Published online: 15 March 2023

Abstract

Computational thinking (CT) is gaining attention in education as a part of digital literacy and can be addressed in several disciplines, including mathematics. Through the lens of Brennan and Resnick's framework, we investigated how computational concepts, practices, and perspectives can be addressed in upper-secondary statistics lessons using spreadsheets through design-based research. Three classes of, in total, 58 16- to 17-year-old 11th-grade students explored several authentic real-life data sets in three 2-h sessions using spreadsheets. We evaluated the intervention by analyzing students' workbooks, spreadsheet files, interviews, and questionnaires. The findings indicate that (1) students successfully engaged in computational concepts through using formulas, parameters, and conditional statements, (2) fruitfully applied data practices, and (3) demonstrated awareness of the relevance of CT for their everyday and future lives. These results highlight the potential of the use of spreadsheets in secondary school for developing computational thinking skills. Implications for further integration of CT in the mathematics curriculum are discussed.

Keywords Computational concepts · Computational practices · Computational perspectives · Computational thinking · Mathematics education · Spreadsheets

✉ Sylvia Patricia van Borkulo
s.vanborkulo@uu.nl

[1] Utrecht University, Utrecht, The Netherlands

[2] Radboud University, Nijmegen, The Netherlands

[3] Erik Barendsen, Radboud University, Nijmegen & Open University of the Netherlands, Heerlen, The Netherlands

[4] Netherlands Institute for Curriculum Development, Amersfoort, The Netherlands

Introduction

Digital literacy is an essential skill in our increasingly digital twenty-first-century society. Computational thinking (CT) emerged as part of digital literacy and led to many initiatives to embed CT in the K-12 curriculum (Yadav et al., 2016). CT was defined as a problem-solving approach, employing concepts originating from computer science (Wing, 2006). Wing argued that CT is a universally applicable skill set not just for computer scientists but also useful for everyone. More generally, computation can be seen as a lens for looking at the world (Denning, 2009). In light of this universal application, CT skills are acknowledged as relevant and important for citizens and professionals in today's society. As a consequence, computational thinking is gaining attention in education.

Many dedicated courses for acquiring CT skills have been developed, for example, by programming robots (Atmatzidou & Demetriadis, 2016) or by programming in Scratch (Zhang & Nouri, 2019; Pérez-Marin et al., 2020). However, CT might also be addressed through existing school subjects' curricula (Bocconi et al., 2016). For example, initiatives have been taken for integration in Science, Technology, Engineering, Arts and Mathematics (STEAM) fields (Lee & Malyn-Smith, 2020; Lee et al., 2020), music (Bell & Bell, 2018), biology (Arastoopour Irgens et al., 2020), and physics (Hutchins et al., 2020).

Because of the common grounds of mathematics and CT, mathematics is a natural candidate within school subjects to address CT aspects (Chan et al., 2022; Kallia et al., 2021). Research has been done on the integration of CT for the topics of geometry (Kynigos & Grizioti, 2018), early algebraic thinking (Bråting & Kilhamn, 2021), probability and statistics in an unplugged way (Costa et al., 2017), and with use of a wide range of tools, such as Scratch (Bigotte de Almeida et al., 2017; Calao et al., 2015), dynamic geometry software (Sinclair & Patterson, 2018), Logo (Kynigos & Grizioti, 2018), and programming in Python on a graphing calculator (Kranz et al., 2012).

Both in mathematics and computer science, data and statistics play a central role. Data analysis and data literacy (Tolboom, 2012) are becoming more important due to the omnipresence of "big" data in society and daily life. To improve data literacy, data science is an important topic to teach, covering the combination of statistical thinking, CT, and mathematics (Gould, 2021). Since statistics is a regular topic in many mathematics curricula (Franklin et al., 2007; Weiland, 2019), it provides opportunities to integrate CT into the mathematics curriculum.

Spreadsheets software is an example of software that can be used to foster computational thinking in a range of mathematical topics, including arithmetic, equations, trigonometry, and statistics (Sanford, 2018). In the case of statistics, the tool provides users the possibility to explore large data by means of calculations and thereby enables users to understand structures in the data and give meaning to what the data represents.

In this study, we research how to address CT in a statistics course within secondary mathematics education. We set up a study following a design-based research approach on the integration of CT concepts and practices in a statistics module for 16- to 17-year-old pre-university students, who enrolled in an applied mathematics course.

Theoretical Background

CT has generally been described as the "ability to engage in problem-solving, designing systems, and understanding human behavior" (Wing, 2006, p. 6). Seeing CT as an attitude and skill set for everyone and not only for computer scientists (Wing, 2006) made CT both highly relevant for educational researchers and, at the same time, a broad construct that is hard to define. Reaching a consensus for a single definition of CT appeared to be difficult in the literature (Haseski et al., 2018). Cuny et al. (2010) suggested the following definition focusing on thought processes: "Computational thinking is the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" (p. 1).

A more specific and operational definition of CT was provided by the Computer Science Teachers Association and the International Society for Technology in Education and focused on CT as a problem-solving process. The definition included the following characteristics (CSTA & ISTE 2011, p. 1):

- Formulating problems in a way that enables us to use a computer and other tools to help solve them;
- Logically organizing and analyzing data;
- Representing data through abstractions such as models and simulations;
- Automating solutions through algorithmic thinking (a series of ordered steps);
- Identifying, analyzing, and implementing possible solutions to achieve the most efficient and effective combination of steps and resources;
- Generalizing and transferring this problem-solving process to a wide variety of problems.

Selby and Woollard (2013) developed the definition of CT further and argued that the definition should include the idea of a thought process, besides the concept of abstraction, and the concept of decomposition. This resulted in defining computational thinking as "an activity, often product oriented, associated with, but not limited to, problem-solving" (p. 5). They addressed computational thinking as a cognitive or thought process that reflects the ability to think in abstractions and generalizations, to think algorithmically, and to think in terms of decomposition and evaluations.

The perspective of seeing computational thinking as different thinking processes has been further developed and investigated. Kallia et al. (2021) concluded from a Delphi study among experts in mathematics and computer science education that CT includes the following thinking processes and can expand beyond this range: abstraction, decomposition, pattern recognition, algorithmic thinking, modeling, logical and analytical thinking, and generalization and evaluation of solutions and strategies.

In contrast to definitions that focus on thinking processes, Brennan and Resnick (2012) took a different stance, which aligns with our view that CT is a skill that is increasingly important in everyday life and work. To mark the multiple facets of CT, Brennan and Resnick developed a framework with three key dimensions of computational thinking in relation to design-based activities: computational concepts, practices, and perspectives. The framework was designed in the context of programming activities with a visual programming language, namely Scratch.

The first dimension, computational concepts, is related to the key principles that a programmer employs when programming. Originally focusing on Scratch programming, computational concepts involved sequences, loops, parallelism, events, conditionals, operators, and data. In the case of using an interactive tool such as Excel, the key concepts involve using Excel formulas with parameters and conditional statements, decomposition to break down a problem into smaller more manageable parts, and pattern recognition to interpret data.

The second dimension, computational practices, relates to practices developed when programming. In the context of programming in Scratch, Brennan and Resnick (2012) mention four main sets of practices: being incremental and iterative, testing and debugging, reusing and remixing, and abstracting and modularizing. In the context of data research using a spreadsheet tool, specific data practices come into play. Data practices have been defined as one of the four main categories in the taxonomy of computational thinking by Weintrop et al. (2016). In that taxonomy, data practices include collecting data, creating data, manipulating data, analyzing data, and visualizing data. From the perspective of modeling data and handling large, rich datasets, Erickson et al., (2019) introduced the term *data moves* to describe the actions needed to handle large data and research data, including filtering, manipulating data, merging data, creating new groupings or new measures to do analyses on datasets. In Excel, it is possible to automate procedures by programming macros. In the study described here, data moves mainly include data filtering, sorting, manipulation, and data representations in the form of charts.

Lastly, the third dimension in Brennan and Resnick's framework concerns computational perspectives and relates to the perspectives programmers form about the world around them and themselves. Computational perspectives include expressing ideas, connecting to other people and their ideas, and questioning how CT makes sense of the world. Computational perspectives are also related to how students perceive technology and the use of digital tools. As Gillott et al. (2020) express, computational perspectives enable students to "(i) create rather consume media; (ii) use digital tools in innovative ways and (iii) question the role of technology in daily life based on an appreciation of the possibilities and limitations afforded by technology." (p. 2). When computational thinking perspectives develop, the learner forms a "computational identity" as was found by Kong and Wang (2019). In the context of a programming course, Kong and Wang distinguished the following subcomponents of computational identity: (1) programming affiliation, (2) programming engagement, (3) programming actualization, and (4) programming goal setting. Furthermore, computational perspectives relate to problem-solving abilities. Chalmers (2018) found that "students developed a computational perspective, while, initially, some students had difficulty when their robot did not perform as planned; most students problem-solved as they identified and debugged issues with their robot build and program" (p. 98) In the context of data research using spreadsheets, students' computational perspective includes seeing the relevance of the researched topic and related datasets. Students are confronted with how data and manipulating data using a computational tool can be used in daily or future life. In addition, students will experience the possibilities and limitations of the tool. The challenges of how to overcome difficulties in problem-solving and how to use the tool in other situations will inform the development of students' computational perspective. In the study presented in this paper, therefore, computational perspectives include the perception of CT and its relevance for daily and future life, acknowledging the opportunities and limitations tools come with.

Many initiatives have been taken to research CT in the mathematics classroom (Lv et al., 2022). The main focus in empirical studies integrating CT and mathematics has been on primary education, and studies concentrate on the topics of geometry and number operations (Lv. et al., 2022). For secondary education, ideas have been developed about addressing CT in statistics, for example, data moves (Erickson et al., 2019), data-scientific thinking (Gould, 2021), and the use of spreadsheets (Valovičová et al., 2020). A link between CT and mathematics might be problem-solving (Finsterbach Kaup, 2022). A problem-solving approach for teaching spreadsheets to develop CT skills appeared to be effective and provided longer-lasting knowledge than the traditional surface, tool-centered approach (Csernoch et al., 2021). More empirical research is needed, however, to extend the knowledge about how to integrate CT in the mathematics classroom for the topic of statistics and data science at the secondary level.

For this study, we used a computational approach to statistics by applying the framework developed by Brennan and Resnick (2012), containing computational concepts, practices, and perspectives in the context of data research. As such, this study aims to add more insight into how to address CT in the high school topic of statistics using spreadsheets. Our research questions are:

1. How can CT concepts and practices be addressed in 11th-grade statistics lessons using spreadsheet software?
2. Concerning computational perspectives, how do students perceive CT and its relevance?

Method

This study followed a design-based research approach (Cobb et al., 2003) and explored the design of a lesson series about integrating CT into mathematics for the topic of statistics.

Research Context and Design

The lesson series was co-designed by the researchers and teachers in a larger project about computational and mathematical thinking. Part of the project investigated the topic of calculus using dynamic geometry software (Van Borkulo et al., 2021). The study reported in the present paper handles the topic of statistics using spreadsheets. This topic aligns with the subject of statistics, which is an important part of the program for the stream of applied mathematics in the Dutch curriculum that focuses on informal mathematics, modeling, and real-life applications, and is offered to students in the school education track that prepares for social sciences and humanities. The project aimed to explore ways to involve more students in CT activities by broadening the scope toward other school subjects and focusing on more diverse content. This is especially relevant in the Netherlands, since computing is not a mandatory part of the curriculum.

The activities address both computational and mathematical thinking in the mathematics classroom and focus on using a digital tool rather than coding or programming. We aimed to integrate CT in "conventional" mathematics curricula using commonly used and accessible mathematical tooling, such as spreadsheets, to convince teachers of the interest and to acknowledge time constraints. Since the development of CT skills seems to benefit from combining digital "plugged" computer approaches and non-digital "unplugged" approaches (Caeli & Yadav 2020), we sought a balance between plugged and unplugged activities in the design. The unplugged activities focus on defining the steps in the problem-solving process, i.e., how to analyze data to answer a question about the data, determine which mathematical concepts are needed, and how to use the tool to get the results and reflect on the outcomes. The plugged activities focus on using spreadsheets and their functions to explore and analyze data. We employ the tool Excel to make students use digital tools that are relevant for both mathematics and their future life and, at the same time, are accessible to students, teachers, and the school. Excel has a low threshold to use, because students and teachers generally have some experience in using Excel. Alternatives considered were R, which has many features but requires too much extra learning for the students and teachers, or Jupyter notebooks, which involve technology that is not commonly used in schools.

To help students with the use of the tool Excel, we added scaffolding introductory activities. In the iterative process of designing the materials, we decided to add even more scaffolding in the form of detailed stepwise instructions related to the use of Excel, as we initially overestimated students' skills in using spreadsheets. However, the scaffolding appeared to be too fine-grained for students who already have some skills in Excel. Therefore, in the final version of the lesson series presented in this paper, we offered some scaffolding in the form of an Excel cheat sheet, in which they could look up information, examples, tips, and tricks that were relevant to the given tasks.

The focus of the lesson series is on the CT aspects of problem-solving, data moves, and algorithmic thinking. The aspect of problem-solving is employed by using Excel as an investigation tool. Data moves are implemented in sorting, selecting, filtering, recoding, and aggregating data. Algorithmic thinking is addressed by translating the data analysis steps into computational solutions and by using Excel formulas. Formulas in Excel are commands that help to compute data characteristics, for example, the mean of some set of numbers or the number of occurrences of a specific string among a data column. Formulas help students in the process of generalization in the sense that students see the outcome of a formula changing when the data changes or when parameters or conditions are changed. An example of a formula using parameters and conditions to determine the number of female adults in a dataset with columns gender (A) and age (B) is COUNTIFS (A:A, "female," B:B, "> = 18"). Setting the parameters and conditions in this formula selects the relevant cases. In this case, the cases are counted for which column A contains the value "female," and the number in column B is equal to or above 18.

The lesson series that the students worked on consisted of two parts (see lesson materials on https://surfdrive.surf.nl/files/index.php/s/y3IkEr45TFHuIC1). The first part was about the dataset of the Titanic (https://surfdrive.surf.nl/files/index.php/s/6pFgL7pKs6dEycE) containing passenger information (see Fig. 1) and asked students to investigate factors that influenced the survival rate. The leading question was "Women and children first?." Students needed to investigate whether or not it was true that women and children were saved first during the Titanic disaster. The second part offered a choice of three different datasets related to school grades to set up an own research question and investigate the data. The second part concluded with writing a report on one's own data research for the dataset of their choice. The Excel cheat sheet with tips and tricks guided the students in the possibilities of using formulas in Excel (see https://surfdrive.surf.nl/files/index.php/s/6pFgL7pKs6dEycE).

In four lessons of 120 min each, the students worked in small groups of two to four students in the workbook and Excel files, providing plugged and unplugged activities. All students were asked to fill in the tasks in their workbooks. The final task in the workbook was to write a report. The tasks in Excel were group work. Some students worked alone if they preferred or, for example, because they worked at home in quarantine.

pclass	survived	name	sex	age
1	1	Allen, Miss. Elisabeth Walton	female	29
1	1	Allison, Master. Hudson Trevor	male	0.9167
1	0	Allison, Miss. Helen Loraine	female	2
1	0	Allison, Mr. Hudson Joshua Creighton	male	30
1	0	Allison, Mrs. Hudson J C (Bessie Waldo Daniels)	female	25
1	1	Anderson, Mr. Harry	male	48
1	1	Andrews, Miss. Kornelia Theodosia	female	63
1	0	Andrews, Mr. Thomas Jr	male	39
1	1	Appleton, Mrs. Edward Dale (Charlotte Lamson)	female	53

Logical_test	E2<age_child	= FALSE
Value_if_true	1	= 1
Value_if_false	0	= 0

isChild	parameter	
0	age child	13

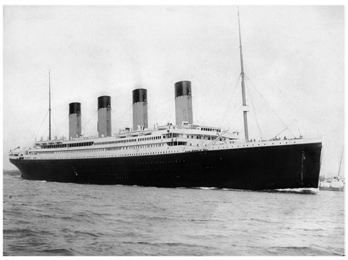

Fig. 1 Snapshot of the Titanic dataset (picture by Francis Godolphin Osbourne Stuart—http://www.uwants.com/viewthread.php?tid=3817223&extra=page%3D1). *Note*: This figure demonstrates part of the Titanic dataset (with columns passenger class (pclass), survived, passenger name, sex, and age (in years, fractional if age less than 1)), and an example of how conditional statements can be used

Participants

The participants in the study were 58 pre-university students aged 16 to 17 years from three classes with two teachers, recruited from one of the project's partner schools, a middle-sized school in the Netherlands. The students had taken an Excel course in a previous school year in which they learned the basics of Excel, such as entering, sorting, and filtering data, creating columns, adding graphs and tables, and using basic statistical formulas, such as AVERAGE and MEDIAN. The course followed a directive approach and guided the students step by step in what they needed to do and where to click. Coming from different school education tracks, the specific moment of the Excel course differed slightly among the students.

Data Collection and Analysis

To evaluate the feasibility of our design, the workbooks and Excel files were analyzed with respect to the completeness of the answers and with respect to computational concepts and practices.

We studied the students' learning experiences in the CT-embedded lesson series about using spreadsheets in statistics. To investigate students' perceptions of computational practices, concepts, and perspectives, we conducted semi-structured interviews. In the last of the four lessons, we invited all students, and 27 students voluntarily participated individually in semi-structured interviews about their perception of the lesson series and learning CT and how they handled data moves in the tasks (see Table 1). Depending on the student's perspective, which is hard to ask for directly, follow-up questions were asked to deepen emerging topics. All interviews were recorded and transcribed and then coded. The coding process took Brennan and Resnick's framework of computational concepts, practices, and perspectives as a starting point and grouped codes into categories. For example, the quotation "*if you make a small mistake in the Excel formulas, the whole answer was wrong and I found it hard to find the mistakes I made*" was coded as "syntax problems," grouped into the category "formulas" and organized under "computational concepts." Thereby, we gave space for themes to emerge and to frame them into the framework of computational concepts, practices, and perspectives. The coding process was performed by two researchers in continuous collaboration and discussion to ensure agreement.

After the lesson series, we administered a 15-min questionnaire about previous experience with Excel and programming and the students' perceptions of aspects of the lesson series, such as difficulty and importance (see Table 2). All students were invited to complete the questionnaire, and 49 students voluntarily participated.

Overall, the data included digital workbooks (58 students), reports (38 students), Excel files (16 groups), questionnaires (49 students), both teachers' logbooks, and interview transcriptions (27 students, see Table 3). The used code themes in the analysis of the interviews and their frequencies are listed in Table 4.

Table 1 Main questions in semi-structured student interviews

Question topic	Question
General	How did it go? What did you run into?
	What do you think about Excel for these kinds of problems?
On tasks in general	How did you use formulas?
	How did you use diagrams?
	How did you explore other factors?
	How did you tackle the problem?
	What difficulties did you encounter? And how did you solve them?
	Would you do anything differently next time?
	Can this approach also be used for another problem?
Specifically on grades tasks	What dataset did you choose? And why?
	How was it to find your own problem?
	What did you do to explore or edit the data and why?
Reflection on CT in math	What do you think of the lesson series about CT?
	Can you describe what you learned in general in this lesson series? And how it might help you in solving problems in the future?
	How did you develop aspects of CT in the lesson series?

Results

The results of the study are organized into a general section about student achievement, then sections computational concepts and computational practices that both address the first research question, and finally a section about computational perspectives that address the second research question.

General Impression of Student Achievement

Overall, most students were able to complete the tasks in the lesson series, indicating the feasibility of the design of the lesson series. The average success rate for the Titanic tasks was 82%. The second part about grades had more missing data because of time limitations and had an average success rate of 66%. The last task of the grades part, writing a report, was completed by 38 students. The reports were mainly short essays of one or two pages (36 of 38 reports), and two reports were extensive (four to seven pages).

Computational Concepts

The computational concepts that students employed in solving problems using Excel as an investigation tool (see research question 1) were related to using

Table 2 Questions in the student questionnaire

Item and item type	Topic
Degree of previous experience (1. No experience, 2. Seen other people use it, 3. Worked with it, 4. Lot of experience)	Experience with Excel
	Experience with Programming
Degree of agreement for general aspects of the lessons (1. Strongly disagree, 2. Disagree, 3. Neutral, 4. Agree, 5. Strongly agree)	"I think mathematics is important for my future"
	"I feel confident when working on mathematics assignments"
	"I feel confident working with computers and digital tools"
	"I feel confident when I program"
	"I enjoyed working on the assignments"
	"I wish the lesson series was longer"
	"I wish the lesson series was shorter"
	"There was enough time to complete the assignments"
	"I understood the assignments"
	"I like the lesson series more than regular mathematics classes"
Degree of perceived difficulty (1. Very difficult, 2. Difficult, 3. Neutral, 4. Easy, 5. Very easy)	Formulas Excel
	Parameters Excel
	Conditions
	Diagrams
	Statistics
	Data analysis
	Normal distribution
	Relation between factors
Degree of use of resources (1. Never, 2. Once, 3. Sometimes, 4. Often)	Workbook
	Teacher
	Peer students
	Internet
	Parents/carers
Open ended	What advantages do you see in using Excel to solve problems in mathematics?
	What disadvantages do you see in using Excel to solve problems in mathematics?
	What did you learn in general in this lesson series about CT? And how may it help you solve problems in the future?

Table 3 Overview of data sources and relation with research questions

Data source (number)	RQ1: CT concepts and practices	RQ2: CT perceptions
Workbooks (58, individual work)	X	
Reports (38, individual work)	X	
Excel files (16, group work)	X	
Interviews (27)	X	X
Questionnaires (49)	X	X

Table 4 Overview of interview code themes, categories, and frequencies in interview transcriptions

Code themes	Categories	Frequency
Computational concepts	Formulas	70
	Conditional statements incl. parameters	8
Computational practices	Data moves—filter	9
	Data moves—sort	24
	Data moves—manipulation	14
	Data moves—representations/diagrams	18
Computational perspectives	View on CT	39
	Difference with regular maths	35
	Advantages Excel	44
	Disadvantages Excel	28
	Relevance daily and future life	51
	Data set choice	34

formulas and, more specifically, to using parameters and conditional statements within formulas in Excel.

Formulas

To investigate the Titanic dataset and factors that influenced the survival rate, the relevant formula to be used was COUNTIFS with various criteria, for which they could find information in the cheat sheet. In the Titanic tasks, most students used Excel formulas to do calculations; 55% described formulas in the workbook, and 88% demonstrated the use of formulas in the Excel file, 75% correctly. The second part about grades gave students the freedom to choose their research question and led to less-frequent use of formulas. In the final report about their own investigations, 63% described the use of Excel formulas: 50% used AVERAGE, and 11% used COUNTIFS.

In the interviews, we inquired the students' ideas about the formulas and how they used them. In general, the use of the formula COUNTIFS was discussed with 24 of the 27 students. The use of formulas was most frequently mentioned as a difficult part of the tasks (20), 8 times it was mentioned as easy. The challenges students encountered related to using Excel formulas were syntax problems (8 students), caused by typing errors or using wrong characters, for example, a wrong separator (";" versus ":"), and the use of criteria (7 students). The cheat sheet helped in using the formula correctly (6 students mentioned this explicitly). Other resources mentioned were watching videos about how to use formulas (2 students) and asking the teacher (1 student). In addition to the interview data, in the questionnaire, more than 73% of the students reported that the teacher helped them sometimes or often, and almost half of the students (57%) indicated that they used the internet for help sometimes or often. Apparently, the lesson design and the teaching setting invited a collaborative learning approach.

Besides Titanic passengers' gender and age combinedly influencing the survival rate (following from the task's question "women and children first?"), other factors that were investigated during the Titanic tasks were age as a singular variable and passenger class, respectively. In investigating these additional factors, the workbooks showed that only 8 students used Excel formulas, 14 used a frequency table, and the rest used less-specific strategies to answer the questions, such as sorting or calculating percentages without using Excel formulas. It seemed that applying the previously frequently used formula COUNTIFS in a different situation was hard and not trivial for the students.

Parameters

In the Titanic tasks, students started with calculating the number of survivors using the formula COUNTIFS. In this formula, they had to indicate relevant column parameters to differentiate between adults and children, and survivors and non-survivors, respectively. In the questionnaire, more than half of the students (57%) reported that the use of parameters in formulas in Excel was difficult or very difficult. Nevertheless, despite this perceived difficulty of using parameters, in the Excel files, 12 of the 14 groups showed a correct use of COUNTIFS. Apparently, students used several resources, mostly the teacher and peers, to overcome the difficulties as indicated in the questionnaire (see Fig. 2). More specifically, in the interviews, 11 students mentioned using the cheat sheet in case they did not exactly know how to use a formula.

Figure 3 below shows an excerpt from a student's workbook, describing the use of COUNTIFS for investigating whether women and children were saved first. This student used the cells G8, G9, and G10 as variables to define the COUNTIFS formula's criteria for the columns survived, gender, and age, respectively. The listed cells contain the values that are used in the comparison of the criteria. The use of parameters in COUNTIFS required the students to apply logical thinking and use conditional statements. In addition, this student created a more general solution by using variables.

Conditional Statements

To answer the tasks about the Titanic dataset, it was necessary to use multiple conditional statements. This was experienced as difficult by the students. In the questionnaire, almost a third of the students reported the use of conditional statements as difficult to very difficult (33%). In the interviews, seven students mentioned conditional statements as being difficult. For example, one student said: "*But when you*

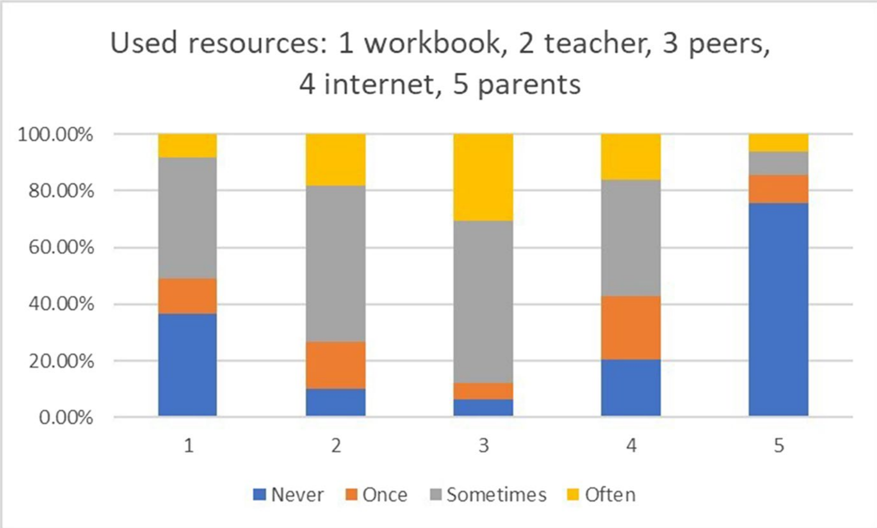

Fig. 2 Used resources as indicated by the students in the questionnaire

G8 = 1
G9 = male
G10 = <18

And then
=COUNTIFS(B2:B1310, G8, D2:D1310, G9, E2:E1310, G10) gives 31 boys (result in I8)

Fig. 3 Excerpt from the workbook of a student, Titanic task 5 (with columns B, survived; D, gender; and G, age)

have to use multiple criteria, it gets a bit more complicated. Which column should you select then? Then you do from 1 to something, but do you have to take the same criteria from one column? Or can you take criteria from the other column? That's where I got a little stuck. But eventually, I figured it out."

Computational Practices

The main computational practice that the students engaged in was the practice of data moves, including data exploration, manipulation, filtering, sorting, and representing data in tables and diagrams. The Excel files showed for the Titanic tasks that almost all students used sorting to explore the data (15 of the 16 Excel files included sorting) and used formulas to find the number of survivors for the different groups of passengers (14 of the 16 Excel files). The Excel files, furthermore, showed data manipulation in the form of the creation of a new column, defining categories for variables, and, for a small part, the use of graphics (see Fig. 4). The data practices reflected in the reports were the manipulation of data (60%) and the use of graphics (23%).

Data Moves: Filter

The use of data practices was also reflected in the workbooks and the interviews, especially for the Titanic part. For example, in the interviews, five students elaborated on the process of filtering, and nine students the process of sorting in finding the numbers. One student explained how she used filtering in investigating the influence of passenger class on the survival rate: "if you have a column, then there is this triangle you can click. I had clicked, for example, class and then you saw that more people had survived in the first class than in the third class." Another student stated he encountered problems when using filters: "*Then I tried to calculate the average for each year, but I kept finding the same answer.*" For most students, filtering and sorting served as orientations on the dataset. As a student explained in the interview, filtering by clicking different values in the column header helped her gain insight into the data, and she used it to be able to use a formula correctly as a next step.

However, some students seemed to avoid the use of formulas and conditions and used filtering less efficiently. In the interviews, two students explicitly mentioned using techniques that hindered finding exact answers. One student explained the use of scrolling: "*We hadn't done that (use a conditional statement). We had just sorted and then looked at what is where.*", "*We had just looked, first sorted, and then we had noted the numbers (…) and then how many on average survived.*" Another student used estimation techniques to approximate the answer: "*You can just look very quickly, if you see survivors, a lot of women who didn't survive, you can just look*

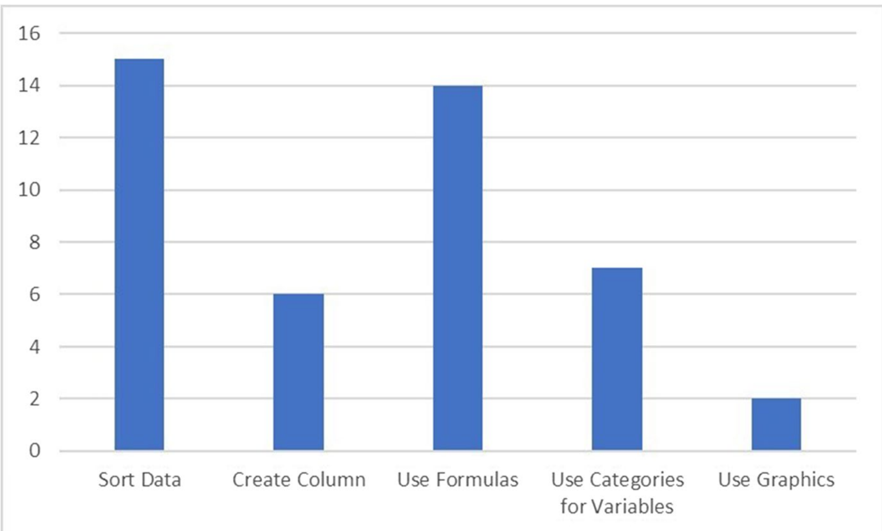

Fig. 4 Number of student groups demonstrating data moves in Titanic Excel file ($N = 16$)

that way. Not really counted per se." Filtering is a useful way to gain insight into the structure of the data. Nevertheless, it appeared to be an insufficient technique to solve the problem at hand, leading this student to not find an exact answer.

Data Moves: Sort

A technique that was less efficient, but often resulted in a correct answer, was sorting and then copying and pasting a selection of the data to another data sheet, as described by a student: "*sorted again and then… I don't remember very precisely, but I think all the (passenger) classes are in another tab.*" When asked if she would do it the same way next time, the student answered "*I would rather use formulas for that though, like that COUNTIFS, but I didn't really know how that worked yet.*" In this case, the limitations of the sorting technique made the student realize that formulas are a more efficient way to do calculations.

Data Moves: Representations

In the Titanic tasks, the results were mainly represented in tables and numbers. Only two groups included graphs in their Excel sheets. In the grades tasks, students had more freedom to choose their own problem approach, and this inclined more students to use graphical representations of their results. More specifically, in the grades reports, students demonstrated what they have learned in the dataset of their own choice with their own research question, for which nine students used graphics.

Computational Perspectives

In the context of computational perspectives, we investigated the perceptions of the students with respect to the relevance of CT for their future life and their perceptions of the learning of CT in the lesson series and the use of Excel.

Students' Perception of Relevance for Daily and Future Life

When talking about the added value of the lesson series and the topic of computational thinking and statistics, the relevance of using Excel for data science in daily or future life was mentioned by 14 of 27 students in the interviews. In the interviews, the reasons mentioned why they think it is relevant were: you might use it in future jobs, it helps you track personal finances, it is about real problems with real data, and might give insight into Corona infections, for example, it helps to handle large datasets. In the questionnaire, almost half of the students (49%) mentioned that what they learned in the lesson series about CT was useful for their future life or study.

About the use of Excel in mathematics lessons, the following advantages were mentioned in the questionnaire related to the usefulness of technology for problem solving and understanding: learning to handle large data, helping you calculate and compare, requiring less effort, and preparing you for the digital future. Disadvantages of using Excel in mathematics mentioned in the questionnaire were the tool is complicated, you need technical skills and knowledge of the tool, debugging can be a hassle, and it takes time from the exam topics.

In the interview, one student had a nuanced view that learning Excel is handy for future life, but that there must be a purpose for using it. In the questionnaire, students acknowledged that you need technical equipment in the class and that students need specific technical skills to use a tool such as Excel. Using technology might distract some, a student remarked.

In the second part of the lesson series, the relevance for the students' daily file came into play when students chose a dataset and worked on a research question of their own choices. Choosing a dataset was valued as fun or interesting by 10 students. One student explained about the second part: "*You could choose more yourself. You had more of your own influence. Normally, you just have to do what the book says and now you could think of your own questions. That was more fun, because you could explore following your own interests, like going out. Of course, we came up with those questions ourselves. That does make it more fun than just answering questions.*" Another student explained how the second part about researching a question of their own choice increased motivation: "*we wanted to look at the relationship between school level and free time. I thought that was kind of interesting. How much of an impact that had on your free time, so we're going to look at that. Then you can see for yourself where your interest lies. If you do something, which you don't like, then you're not going to like doing it. Then you won't put more energy into it.*"

Students' Views on CT

In general, students positively valued working on CT in the lesson series. In the questionnaire, 71% of the students were neutral or positive with respect to the lesson series. In the interviews, 14 students explicitly mentioned it was fun. The positive remarks include something new, eye opening, from real life, being more independent, thinking for yourself, and letting the computer work for you. Five students explicitly stated that they did not like the lesson series. The reasons they mentioned for their negative responses were feeling like a guinea pig instead of learning something, not having clear guidelines on how to solve the tasks, not liking mathematics at all, and having a preference to write by hand. One student noticed that she liked the topic of data research but just did not like changes so much.

The difference with regular mathematics tasks was positively valued by 15 students in the interviews. For example, one student really enjoyed the project and expressed in the interview that this lesson series gave her a new perspective on things and some "flair" to the learning. The new approach gave her a perspective on how to use mathematics and Excel to solve problems in realistic situations, what she called *"perspective on reality."* In the questionnaire, this student stated that the way Excel was used in this lesson series gave better preparation for future jobs than normal lessons.

With respect to the use of the tool Excel for learning CT, advantages were mentioned 44 times in the interviews by all except one student (26 students). The advantages mentioned in the interviews were that it is useful for gaining insight, having an overview, structuring large datasets, working faster, and having formulas. For example, one student expressed that Excel is useful for organizing large data, when it is impossible to calculate things by hand.

The disadvantages of using Excel were mentioned in the interviews 28 times by 15 students, for example, that you need the skills to use the tool, that you have to know the formulas, that there are so many formulas—it is hard to pick the correct one, and the disadvantage of lacking overview. A student mentioned "*if you type in a formula Excel, (…) you cannot actually see what it's doing. And so I think that's why for me to work with workbooks is better.*" Another student expressed that using Excel might cause frustration: "*If you can do it, I think it's helpful, but if you can't, it's super-frustrating*."

In the interviews, we asked students about their views on CT. The concept of CT was only shortly introduced in the lessons series and mainly addressed by practicing the approach and building understanding during the tasks. After the lesson series, the students appeared to have developed ideas on the concept of CT. Computational thinking was mainly perceived as a step-by-step problem-solving approach (mentioned by 12 students in the interviews), or, more generally, as a different kind of thinking (three students). For example, one student perceived CT as "*logical, step-by-step thinking, in a way that you observe a problem, see how you could solve it, try to solve it, and then see how successful it is compared to the original.*" She expressed that this is not new to her but more sophisticated or fine-grained than she was used to, i.e., looking accurately step-by-step.

Strategies were an important factor in computational problem solving. Students applied different strategies to solve the tasks in the lesson series. For example, in the interviews, breaking down the problem into easier pieces was mentioned by a student: *"And then finally we just made it a little easier. Then it worked out."* Another relevant strategy that appeared to be a useful problem-solving strategy in the context of CT tasks was persistence. One student described an encountered difficulty in Excel: she had selected the wrong cell as a parameter in a formula in Excel, and she interpreted the result as apparently incorrect. To solve the problem, she applied the strategy to step back and try again: she went back to the data, started at the last point where things were still correct, and then tried again. This led to the correct answer. In the end, she thought it was fun to solve the issues and felt a satisfying "I did it!" when she succeeded. Furthermore, the same student thought it was not always clear what she was supposed to do during the tasks in the lesson series. Sometimes, she could not see the forest for the trees, but her strategy to persist and approach the problem differently appeared effective ("*one way or the other*"). Another student mentioned that the lessons were about "*Thinking about the problem differently and finding a solution to it.*"

Conclusion and Discussion

Reflections on Results

In this study, following the framework of Brennan and Resnick (2012), we researched how computational concepts, practices, and perspectives could illustrate the learning of CT and the impact on students' perspectives on CT. In general, the findings show that the lesson series for 16- to 17-year-old pre-university education students was feasible and triggered computational thinking learning processes related to data research. Moreover, the use of a common tool such as Excel in researching familiar, real-life data seemed fruitful and the lesson series triggered awareness of the relevance of CT in real life.

Concerning the first research question on how CT concepts and practices can be addressed in 11th-grade statistics lessons using spreadsheet software, we conclude from the results that students were able to combine data using formulas with parameters and conditions to extract information about the dataset and solve the problems. At first, students encountered difficulties, especially when using multiple conditional statements, which is a known issue in human reasoning (Byrne & Johnson-Laird, 2009). However, with the help of the workbook, the teacher, peers, and resources, such as the cheat sheet and online documentation, they succeeded for the most part. The duration of the intervention was limited and, therefore, also the extent to which students used the possibilities of the tool, e.g., the number of formulas used. Therefore, we conclude that the first steps in employing CT concepts and practices have been made.

Nevertheless, the efficiency of data practices could be improved for many students. We often saw students sort and calculate on a specific range, while, in the next step in problem-solving, they changed the sorting, and the calculations were out of date. This is a weak point in the spreadsheet calculation, a so-called *smell* (Hermans et al., 2012. In the example, one change in the spreadsheet often resulted in the need to make a lot of little changes in several places. More awareness of these pitfalls would improve the use of the tool and steer the computational thinking process. The assessment of the quality of a spreadsheet is a relevant issue and important in future professional life. This issue especially comes into play when working with different worksheets, as the students did in the second part choosing the dataset of their own interest. Therefore, an additional focus on the quality of the solution would have added value.

More in general, the technical skills to use a tool such as a spreadsheet tool in a proficient way are crucial for successful computational problem-solving, as appeared during the design process of the materials in our study and from the results of the intervention in the classroom. Although we live in a digital society where technology is omnipresent, digital skills are not easily acquired or trivial (Kirschner & De Bruyckere, 2017). Before being able to solve problems using a tool, students need a certain level of skills and knowledge of the tool. Our design with the scaffolding of the tasks and the cheat sheet enabled the students, who had a wide variety of prior knowledge, to connect to their level of understanding and to complete missing knowledge. The cheat sheet was used according to the individual needs of the students and appeared to be effective.

Concerning the second research question about computational perspectives on how students perceive CT and its relevance, the study revealed some interesting prospects. From the questionnaire and the interviews, when reflecting on the use of tools and addressing CT in the mathematics lessons, students showed a high level of awareness of the relevance of the use of spreadsheets and CT in mathematics and a positive perception of the benefits of CT and its importance for their (future) work and daily life. Indeed, there is an important relationship between mathematics and daily life in the sense that mathematics prepares for real-life challenges (Jawad, 2022). In addition, offering real-life problems is an effective pedagogical approach to developing CT skills (Bocconi et al., 2022). However, it was not always clear to the students what exactly it was that they were learning. On the one hand, students were familiar with the topic of data analysis and the tool Excel; on the other hand, the computational approach was new and required some experimentation with the tool to find solutions. This might have confused students with respect to the aimed learning goals. Despite these ambiguities, most students showed awareness of the importance of the CT approach.

An additional notable finding related to computational perspectives was that not everyone appreciated the new approach. One student felt like a "guinea pig," but most students valued working on developing new skills on relevant topics from real life. Following one's own interests in the second part by having some freedom in choosing one's own dataset and related research question was very stimulating and seemed to connect the students' learning to their own interests. This is in line with the finding that providing relevant contexts and personalized instruction for students' interests is a powerful way to support learning and, thereby, motivate students (Walkington, 2013). Motivation affects persistence in learning (Vollmeyer & Rheinberg, 2000), and this is an interesting and relevant mechanism, since we found that the problem-solving process in the CT tasks required creativity and persistence to succeed. It would be worthwhile to investigate the relation between motivation and persistence to see how to enhance students' computational problem-solving skills.

Limitations of the Study

Overall, the study showed the potential of using spreadsheets at secondary school for developing computational concepts, practices, and perspectives. However, the study also had some limitations. The study was performed in one school with three classes with two highly motivated teachers that voluntarily participated in the project. This situation is not representative of schools in the Netherlands. A second limitation was the Corona pandemic, which influenced the presence and participation of students. While it was possible to do in-depth, qualitative research in this smaller-scale setting, it would be interesting to perform the teaching experiments in more neutral circumstances and to investigate the learning gains more quantitatively over a longer period. Furthermore, with respect to the students' perspectives, we only unveiled students' initial views on CT and its relevance in their lives. Further research over a longer period of time is needed to investigate the development of students' computational perspectives in more detail and inquire possible shifts in their perspectives.

Implications for Educational Practice

In reflection on these conclusions, we see some implications for educational practice. With the overarching goal to prepare all members of our society for the challenges related to our current digital age, an important aspect to take into account is the diversity among people and broadening participation in computing to different people. Diversity can be dealt with in education, for example, by paying attention to people with different interests, e.g., sciences- vs. humanities-oriented people as researched by Katai (2020), or computer science vs. non-computer science-oriented people (Hsu et al., 2021), and other groups are, of course, conceivable. In our study, we aimed to involve more students in CT activities by broadening the scope toward other school subjects such as mathematics and focusing on more diverse content. Different student interests were addressed in the open second part of the lesson series where students choose their own topics and research questions. This could be developed further by adding a larger variety of datasets including both sciences and humanities topics, among other topics. Students might also take a more active role and create their own datasets and work on more personally meaningful data. This might also address different people with different cognitive styles and different learning levels.

When integrating CT into learning activities in another subject such as mathematics, an important aspect is the assessment of the learning gains of CT activities (Bortz et al., 2020). Especially, when two fields of learning, CT and mathematics, are in play, it appears hard to measure learning gains. Bortz et al. (2020) emphasize the importance of assessment approaches that reflect "multiple ways of knowing and doing," for example, by using integrated assessment tasks on the one hand and, on the other hand, also use items that assess multiple facets from each domain that are not fully integrated. Assessment issues are also addressed by Weintrop et al. (2014) who promote authentic assessment in the context of CT integrated into STEM classrooms. Further studies might put focus on efficient assessment methods by developing a variety of assessment items, in addition to reviewing student work from the instruction, such as workbooks and Excel files.

Outlook on Future Research

In conclusion, this study provides a better view on what to teach when learning CT by providing concrete starting points for the integration of computational concepts, practices, and perspectives in mathematics topics relating to authentic contexts. Since CT is a fundamental skill that requires continuous development, it is a time-consuming process that involves repeated practice. Further studies need to explore how CT skills in the context of spreadsheets can be further developed and how CT can be integrated into other parts of the mathematics curriculum touching different topics. It would be worthwhile to explore how relevant contexts with respect to student interests and the real world can be addressed in meaningful computational problem-solving within mathematics subjects, addressing the topics of motivation and diversity and thereby broadening participation in the field of computing.

Author Contribution Sylvia Patricia van Borkulo, Christos Chytas, Paul Drijvers, Erik Barendsen, and Jos Tolboom contributed to the design of the study. Sylvia Patricia van Borkulo and Christos Chytas performed the experiments in the school and wrote the main manuscript text. Sylvia Patricia van Borkulo

prepared all figures and tables. Sylvia Patricia van Borkulo, Christos Chytas, Paul Drijvers, Erik Barendsen, and Jos Tolboom reviewed the manuscript and approved for submission.

Funding The research reported here was part of a larger project granted by the Netherlands Initiative for Education Research, project number 00517751.

Data Availability The data from this study are not publicly available, but the data can be accessed on request from Sylvia Patricia van Borkulo. All data is stored according to the Data Management Protocol of the Freudenthal Institute of Utrecht University, The Netherlands.

Declarations

Ethical Approval and Consent to Participate We took ethical considerations into account and made significant efforts to ensure the implementation of good research practices for underage populations. Written informed consent was obtained from the participants of the study.

Conflict of Interest The authors declare no competing interests.

References

Arastoopour Irgens, G., Dabholkar, S., Bain, C., Woods, P., Hall, K., Swanson, H., Horn, M., & Wilensky, U. (2020). Modeling and measuring high school students' computational thinking practices in science. *Journal of Science Education and Technology, 29*(1), 137–161. https://doi.org/10.1007/s10956-020-09811-1

Atmatzidou, S., & Demetriadis, S. (2016). Advancing students' computational thinking skills through educational robotics: A study on age and gender relevant differences. *Robotics and Autonomous Systems, 75*, 661–670. https://doi.org/10.1016/j.robot.2015.10.008

Bell, J., & Bell, T. (2018). Integrating computational thinking with a music education context. *Informatics in Education, 17*(2), 151–166. https://doi.org/10.15388/infedu.2018.09

Bigotte de Almeida, E., Gomes, A., Correia, F., & Almeida, R. (2017). MathScratch - Bringing programming and mathematical skills into higher education. In L. Gómez Chova, A. López Martínez, I. Candel Torres (Eds.), *INTED2017 Proceedings* (pp. 7304–7310). IATED Academy. https://doi.org/10.21125/inted.2017.1692

Bocconi, S., Chioccariello, A., Dettori, G., Ferrari, A., & Engelhardt, K. (2016). *Developing computational thinking in compulsory education. Implications for policy and practice* (No. JRC104188). Joint Research Centre. https://ideas.repec.org/p/ipt/iptwpa/jrc104188.html , https://doi.org/10.2791/792158

Bocconi, S., Chioccariello, A., Kampylis, P., Dagienė, V., Wastiau, P., Engelhardt, K., Earp, J., Horvath, M., Jasutė, E., Malagoli, C., Masiulionytė-Dagienė, V., & Stupurienė, G. (2022). *Reviewing Computational Thinking in Compulsory Education.* https://doi.org/10.2760/126955

Bortz, W. W., Gautam, A., Tatar, D., & Lipscomb, K. (2020). Missing in measurement: Why identifying learning in integrated domains is so hard. *Journal of Science Education and Technology, 29*(1), 121–136. https://doi.org/10.1007/s10956-019-09805-8

Bråting, K., & Kilhamn, C. (2021). Exploring the intersection of algebraic and computational thinking. *Mathematical Thinking and Learning, 23*(2), 170–185. https://doi.org/10.1080/10986065.2020.1779012

Brennan, K., & Resnick, M. (2012). New frameworks for studying and assessing the development of computational thinking. *Proceedings of the 2012 Annual Meeting of the American Educational Research Association, Vancouver, Canada*. Retrieved May 29, 2019, from http://scratched.gse.harvard.edu/ct/files/AERA2012.pdf

Byrne, R. M. J., & Johnson-Laird, P. N. (2009). "If" and the problems of conditional reasoning. *Trends in Cognitive Sciences, 13*(7), 282–287. https://doi.org/10.1016/j.tics.2009.04.003

Calao, L. A., Moreno-León, J., Correa, H. E., & Robles, G. (2015). Developing mathematical thinking with scratch an experiment with 6th grade students. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 9307*, 17–27. https://doi.org/10.1007/978-3-319-24258-3_2

Caeli, E. N., & Yadav, A. (2020). Unplugged approaches to computational thinking: a historical perspective. *TechTrends, 64*(1), 29–36. https://doi.org/10.1007/s11528-019-00410-5

Chalmers, C. (2018). Robotics and computational thinking in primary school. *International Journal of Child-Computer Interaction, 17*, 93–100. https://doi.org/10.1016/j.ijcci.2018.06.005

Chan, S.-W., Looi, C.-K., Ho, W. K., & Kim, M. S. (2022). Tools and approaches for integrating computational thinking and mathematics: A scoping review of current empirical studies.*Journal of Educational Computing Research, 60*(8), 1–45. https://doi.org/10.1177/07356331221098793

Cobb, P., Confrey, J., Disessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9–13. https://doi.org/10.3102/0013189X032001009

Costa, E. J. F., Campos, L. M. R. S., & Guerrero, D. D. S. (2017). Computational thinking in mathematics education: A joint approach to encourage problem-solving ability. *47th IEEE Frontiers in Education Conference, FIE 2017*, *2017-October*, 1–8. https://doi.org/10.1109/FIE.2017.8190655

Csernoch, M., Biro, P., & Math, J. (2021). Developing computational thinking skills with algorithm-driven spreadsheeting. *IEEE Access, 9*, 153943–153959. https://doi.org/10.1109/ACCESS.2021.3126757

Cuny, J., Snyder, L., & Wing, J. M. (2010). Demystifying computational thinking for non-computer scientists. *Unpublished manuscript in progress*. Retrieved December 19, 2019, from https://www.cs.cmu.edu/~CompThink/resources/TheLinkWing.pdf.

Denning, P. J. (2009). Beyond computational thinking. *Communications of the ACM*, *52*(6), 28–30. Retrieved December 19, 2019, from https://cacm.acm.org/magazines/2009/6/28490-beyond-computational-thinking/fulltext#

Erickson, T., Wilkerson, M., Finzer, W., & Reichsman, F. (2019). Data moves. *Technology Innovations in Statistics Education, 12*(1). Retrieved April 1, 2021, from https://escholarship.org/uc/item/0mg8m7g6

Finsterbach Kaup, C. (2022). Mapping the relations between computational thinking and mathematics in terms of problem-solving. *Acta Didactica Norden, 16*(4). Retrieved January 19, 2023, from https://journals.uio.no/adnorden/article/view/9185/8355

Franklin, C., Kader, G., Mewborn, D., Moreno, J., Peck, R., Perry, M., & Scheaffer.(2007). *Guidelines for assessment and instruction in statistics education (GAISE) report: A pre-K-12 curriculum framework* (Vol. 9, Issue August 2005). Retrieved June 8, 2022, from www.amstat.org/education/gaise

Gillott, L., Joyce-Gibbons, A., & Hidson, E. (2020). Exploring and comparing computational thinking skills in students who take GCSE Computer Science and those who do not. *International Journal of Computer Science Education in Schools, 3*(4), 3–22. https://doi.org/10.21585/IJCSES.V3I4.77

Gould, R. (2021). Toward data-scientific thinking. *Teaching Statistics, 43*(S1), S11–S22. https://doi.org/10.1111/test.12267

Haseski, H. I., Ilic, U., & Tugtekin, U. (2018). Defining a new 21st century skill-computational thinking: Concepts and trends. *International Education Studies, 11*(4), 29–42. https://doi.org/10.5539/ies.v11n4p29

Hermans, F., Pinzger, M., & van Deursen, A. (2012). *Detecting and visualizing inter-worksheet smells in spreadsheets*. ICSE 2012.

Hsu, T. C., Abelson, H., Patton, E., Chen, S. C., & Chang, H. N. (2021). Self-efficacy and behavior patterns of learners using a real-time collaboration system developed for group programming. *International Journal of Computer-Supported Collaborative Learning, 16*(4), 559–582. https://doi.org/10.1007/S11412-021-09357-3/TABLES/7

Hutchins, N. M., Biswas, G., Maróti, M., Lédeczi, Á., Grover, S., Wolf, R., Blair, K. P., Chin, D., Conlin, L., Basu, S., & McElhaney, K. (2020). C2STEM: A system for synergistic learning of physics and computational thinking. *Journal of Science Education and Technology, 29*(1), 83–100. https://doi.org/10.1007/s10956-019-09804-9

ISTE, & CSTA. (2011). Operational definition of computational thinking for K–12 education. *National Science Foundation*. Retrieved September 14, 2022, from https://cdn.iste.org/www-root/Computational_Thinking_Operational_Definition_ISTE.pdf

Jawad, L. F. (2022). Mathematical connection skills and their relationship with productive thinking among secondary school students. *Periodicals of Engineering and Natural Sciences, 10*(1), 421–430. https://doi.org/10.21533/pen.v10i1.2667

Kallia, M., van Borkulo, S. P., Drijvers, P., Barendsen, E., & Tolboom, J. (2021). Characterising computational thinking in mathematics education: A literature-informed Delphi study. *Research in Mathematics Education, 23*(2), 159–187. https://doi.org/10.1080/14794802.2020.1852104

Katai, Z. (2020). Promoting computational thinking of both sciences- and humanities-oriented students: An instructional and motivational design perspective. *Educational Technology Research and Development, 68*(5), 2239–2261. https://doi.org/10.1007/S11423-020-09766-5

Kirschner, P. A., & de Bruyckere, P. (2017). The myths of the digital native and the multitasker. *Teaching and Teacher Education, 67*, 135–142. https://doi.org/10.1016/J.TATE.2017.06.001

Kong, S. C., & Wang, Y. Q. (2019). Formation of computational identity through computational thinking perspectives development in programming learning: A mediation analysis among primary school students. *Computers in Human Behavior, 106*, 6230. https://doi.org/10.1016/j.chb.2019.106230

Kranz, S., Tabor, C., Duval, A., Lim, K. H., Wagler, A. E., & Freudenthal, E. A. (2012). iMPaCT-Math: Games & activities that motivate exploration of foundational understandings of mathematics concepts while inadvertently scaffolding Computational Thinking and engineered design. In J. Brocato (Ed.), *119th ASEE Annual Conference and Exposition,* Conference *Proceedings*. Retrieved September 14, 2022, from https://peer.asee.org/classroom-games-and-activities-that-motivate-exploration-of-foundational-understandings-of-mathematics-concepts-while-inadvertently-scaffolding-computational-thinking-and-engineered-design.pdf

Kynigos, C., & Grizioti, M. (2018). Programming approaches to Computational Thinking: Integrating Turtle Geometry, Dynamic Manipulation and 3D Space. *Informatics in Education, 17*(2), 321–340. https://doi.org/10.15388/infedu.2018.17

Lee, I., & Malyn-Smith, J. (2020). Computational Thinking integration patterns along the framework defining Computational Thinking from a disciplinary perspective. *Journal of Science Education and Technology, 29*(1), 9–18. https://doi.org/10.1007/s10956-019-09802-x

Lee, I., Grover, S., Martin, F., Pillai, S., & Malyn-Smith, J. (2020). Computational Thinking from a disciplinary perspective: Integrating Computational Thinking in K-12 science, technology, engineering, and mathematics education. *Journal of Science Education and Technology, 29*(1), 1–8. https://doi.org/10.1007/s10956-019-09803-w

Lv, L., Zhong, B., & Liu, X. (2022). A literature review on the empirical studies of the integration of mathematics and computational thinking. *Education and Information Technologies*, 1–23. https://doi.org/10.1007/S10639-022-11518-2

Pérez-Marín, D., Hijón-Neira, R., Bacelo, A., & Pizarro, C. (2020). Can computational thinking be improved by using a methodology based on metaphors and scratch to teach computer programming to children? *Computers in Human Behavior, 105*, 105849. https://doi.org/10.1016/j.chb.2018.12.027

Sanford, J. (2018). Introducing computational thinking through spreadsheets. In M. S. Khine (Ed.), *Computational Thinking in the STEM Disciplines: Foundations and Research Highlights* (pp. 99–124). Springer International Publishing. https://doi.org/10.1007/978-3-319-93566-9_6

Selby, C., & Woollard, J. (2013). Computational thinking: The developing definition. In J. Carter, I. Utting, & A. Clear (Eds.), *ITiCSE 2013: : Proceedings of* the *18th ACM conference on Innovation and technology in computer science education*. Association for Computing Machinery. Retrieved September 13, 2019, from https://eprints.soton.ac.uk/356481/1/Selby_Woollard_bg_soton_eprints.pdf

Sinclair, N., & Patterson, M. (2018). The dynamic geometrisation of computer programming. *Mathematical Thinking and Learning, 20*(1), 54–74. https://doi.org/10.1080/10986065.2018.1403541

Tolboom, J. L. J. (2012). *The potential of a classroom network to support teacher feedback: A study in statistics* education [doctoral dissertation, University of Groningen]. research.rug.nl https://pure.rug.nl/ws/portalfiles/portal/14566051/PhD_thesis_jos_tolboom_definitive5.pdf https://doi.org/10.33612/DISS.14566050

Valovičová, L., Ondruška, J., Chytrý, V., & Medová, J. (2020). Mathematics enhancing Computational Thinking through interdisciplinary STEAM activities using tablets. *Mathematics, 8*(12), 212. https://doi.org/10.3390/math8122128 van Borkulo, S. P., Chytas, C., Drijvers, P., Barendsen, E., & Tolboom, J. L. J. (2021). Computational thinking in the mathematics classroom: Fostering algorithmic thinking and generalization skills using dynamic mathematics software. In M. Berges (Ed.), *The 16th Workshop in Primary and Secondary Computing Education (WiPSCE '21)* (pp. 1–9), October 18–20, 2021, Virtual Event, Germany. Association for Computing Machinery. https://doi.org/10.1145/3481312.3481319

Vollmeyer, R., & Rheinberg, F. (2000). Does motivation affect performance via persistence? *Learning and Instruction, 10*, 293–309. https://doi.org/10.1016/S0959-4752(99)00031-6

Walkington, C. A. (2013). Using adaptive learning technologies to personalize instruction to student interests: The impact of relevant contexts on performance and learning outcomes. *Journal of Educational Psychology, 105*(4), 932–945. https://doi.org/10.1037/a0031882

Weiland, T. (2019). *Critical mathematics education and statistics education: Possibilities for transforming the school mathematics curriculum* (pp. 391–411). Springer. https://doi.org/10.1007/978-3-030-03472-6_18

Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. *Journal of Science Education and Technology, 25*(1), 127–147. https://doi.org/10.1007/s10956-015-9581-5

Weintrop, D., Beheshti, E., Horn, M. S., Orton, K., Trouille, L., Jona, K., & Wilensky, U. (2014). Interactive assessment tools for Computational Thinking in high school STEM classrooms. *Intelligent Technologies for Interactive Entertainment*, 22–25. Retrieved July 13, 2022, from http://ct-stem.northwestern.edu

Wing, J. M. (2006). Computational thinking. *Communications of the ACM, 49*(3), 33–35. https://doi.org/10.1145/1118178.1118215

Yadav, A., Hong, H., & Stephenson, C. (2016). Computational Thinking for all: Pedagogical approaches to embedding 21st century problem solving in K-12 classrooms. *TechTrends, 60*(6), 565–568. https://doi.org/10.1007/s11528-016-0087-7

Zhang, L. C., & Nouri, J. (2019). A systematic review of learning computational thinking through Scratch in K-9. *Computers and Education, 141*, 103607. https://doi.org/10.1016/j.compedu.2019.103607