Technology changing statistics education: Defining possibilities, opportunities and obligations

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Abstract

Data discovery, visualising data and understanding visual representations are important to comprehend a world of large numbers and big datasets. Therefore, applying comprehensive up-to-date methods and considering issues regarding data both small and large are relevant skills for students in order to participate responsibly in the Digital Age. Reviewing various approaches, we outline the current state and recent developments in data discovery and statistics education. Focusing on school curricula and statistical visualization tools, we identify the opportunities for education systems to leverage these technological innovations. In this article, we highlight directions for development and research in this area by offering examples and good practices of current and future concepts to integrate data visualization and Open Data in education from primary through secondary school. Furthermore, considering statistics as a science with multiple facets, we depict approaches to statistics education going beyond conventional single subject boundaries to multi-disciplinary study. Finally, various implications for the teaching and learning of statistics are amplified. In short, the aim of this paper is to define possibilities, opportunities and obligations in statistics education responding to technological advances of the data society.

1 Introduction

The dawn of the digital revolution starting in the beginning of the millennium was foreseen by many authors as having the same consequences in social development as the agricultural and the industrial revolution. In a time of technological revolution, bringing along paradigm shifts and socio-institutional changes, Perez [30] claims that the construction of a new mode of growth due to tech-

nological innovations is characterized by coupling and decoupling a techno-economic and the socio-institutional sphere. The suggestion is to face "the future with a commitment to the construction of a framework capable of making best social use of the new wealth creating potential [...by pursuing] a deep understanding of the characteristics and requirements of the new paradigm" [30, p.23]. Especially over the previous three decades, more and more applications of statistics and data processing have arisen due to technological achievements and the integration of these developments into our society is consequently a serious challenge for the education of future generations.
Nevertheless, regarding these rapid technological innovations, until now, school education, responsible as it is for preparing future generations, has not made enough effort to adopt the paradigm shift of this technological revolution [40]. Society is constantly compromised by the misuse of data and neither political, ethical, social and personal questions arising with a sustainable industry of handling Big Data nor are, with some few exceptions, the methods required to handle data sets reasonably integrated into school curricula [38]. In addition, there has been a massive shortage of data scientists in many application areas and increasing need in companies for knowledge about experimental design, statistical reasoning, and data collection [21] for the past years. As data is often called the 'new oil' bringing opportunities and wealth to society, thus educational research on this topic must be intensified and school curricula have to catch up with these developments. With the growing importance of data for society, innovation of statistics education is more and more promoted by several researchers and organisations recently, providing networks for improving statistics education to assist education in creating a well-informed society, e.g., [29, 40, 11]. As an example, the European project ProCivicStat [12] provides a large collection of teaching materials for data about important social phenomena. Linked interactive visualisation tools give learners the possibility to explore different data sets (e.g., on migration or on human development).

2 Research and practice: Statistics in school education

Research on educational uses of probability theory and statistics is a relatively new development. Beginning in the 1950s the first research in statistics education conducted by Piaget and Inhelder was about the emergence and structural qualities of statistical and probabilistic thinking [18]. In the 1970s the focus of research in stochastics education was on intuitions [14] and heuristics and biases [44] deepened by research on misconceptions regarding various concepts of statistics and probability theory in the 1980s [18]. The main message from the research of this period is that fundamental and firm education in statistics and probability theory, that honestly considers influences of heuristics and intuition, may give alternative possibilities to overcome widespread and persistent biases and misconceptions to develop towards more appropriate ways of recognizing a world where data is becoming more and more important. Therefore, accompanied by the integration of probability theory and also (mostly descriptive) statistics into school curricula in the 1980s and 1990s, subsequent research on the curriculum and the teaching and learning of probability including statistics heralded the current contemporary research period [19].
One of the most referenced frameworks on statistics education (e.g., [5, 18, 38]) worldwide, is built by the Guidelines for Assessment and Instruction in Statistics Education [1, 15], integrating previous research on statistics education as well as research on practising statistics itself introduced by Wild and Pfannkuch [47] in their landmark paper about thoughts occurring in the process of statistical anal-

ysis. Presenting the statistical investigative cycle, the GAISE framework gives recommendations for statistics education that involve teaching statistical thinking with a focus on conceptual understanding, considering statistics as an investigative, student-centred process of analysing multiple variables, and integrating real data by the use of technology to explore and analyse data. Depending on different national traditions on statistics and its education [10], the curricula of Anglo-American countries are strongly influenced by the GAISE framework following a more empirical access to statistics compared to those countries with a strong tradition in deductive stochastics as in Germany or France. In that context, Burrill and Biehler [5] explain the main challenges of teaching statistics and probability theory that is still present in scientific discourse, especially, because of the development and easy access to new technologies. Firstly, ”Probability should not be taught ‘data-free’ but with a view towards its role in statistics. Secondly, data analysis should not be taught completely ‘model-free’ but with a view towards theoretical distributions and underlying processes” [5, p. 61].

Focusing on statistics education, numerous research studies strongly recommend the use of technology in statistics classes, e.g., [3]. It is generally agreed that the teaching and learning of statistics in student-centred problem and inquiry based as well as context based, e.g., [27], learning environments supported by technology [24] and especially by dynamic software [23] is beneficial for developing students' statistical reasoning and improving students' learning of statistics, e.g., [18]. Software such as TinkerPlots [22] and Fathom [13] are specifically designed for educational purposes. Furthermore, there are studies on the benefits of using the Gapminder software, e.g., [25, 34], and other tools. Biehler et al. [3] offer an extensive overview on various types of technological tools used for statistical education highlighting their benefits, purposes and limitations for developing students' statistical reasoning.

Further studies, e.g., [26, 31], with a focus on teachers in statistics education show major problems regarding teachers' knowledge and understanding of statistics and probability theory and how they teach statistics in schools. There are large gaps between research on statistics education, the development of curricula, and the teaching of statistics itself and we rarely come across comprehensive and up-to-date statistics curricula for schools [38]. Reasoning about changing the curricula of statistics education towards a more empirical access implementing technology, Pfannkuch [32] or Pratt et al. [33] stress that, first of all, teacher education must be concerned with issues arising with technological possibilities for school statistics education. Pratt et al. point out factors hindering technological innovation for the use in classes and give reasons for not being convinced that school statistics education will keep up with technical development, with exception of some best-practise works. Despite these concerns, responding to an increasingly data-driven society Ridgway et al. [39] or Watson [46] argue for a profound change in curricula. Good practice examples, e.g., [34, 36, 46, 38, 41] show promising directions to further develop statistics education. These examples from a long list of various activities, projects and studies, have one statement in common: Modern statistics education must deal with visualizations of large data sets using modern technology to fulfil the demands of data society.

As an engaging example, New Zealand's curriculum for mathematics and statistics is recognized by researchers, e.g., [38, 4], as a coherent reaction to the developments of data society.

> *Statistics involves identifying problems that can be explored by the use of appropriate data, designing investigations, collecting data, exploring and using patterns and relationships in data, solving problems, and communicating findings. Statistics also involves interpreting statistical information, evaluating databased arguments, and dealing with uncertainty and variation.* [28, p. 26]

New Zealand's curriculum for mathematics and statistics seems to be explicitly suitable for the needs of learning statistics using real data with context. In each grade, the entire statistical investigative cycle is addressed in some facets – from planning and designing a statistical investigation, reasoning about measurements and collecting data, to visualizing and analysing them and reporting on the findings. Thus, in contrast to many other school curricula for statistics education, worldwide, the statistical investigative process is not split up over many years, but it is fully addressed in each grade, deepening certain aspects.
Due to innovations in processing data, society is concerned in general with political, ethical, social and personal questions arising from these matters. As New Zealand's curriculum shows, innovation of statistics education in schools is possible to prepare society for these quick developments in the data world. Regarding the recent developments in research and teaching practice, Chernoff and Sriraman [6] describe the dawn of a new, fourth phase of research in education of probability theory and statistics. Jones and Thornton [19] are calling it Assimilation Period, where many of the challenges, limitations and possibilities, concerning plural perspectives of statistical data education, will be clarified. As solving problems by searching for information or data, processing, visualizing and analysing it and communicating implications gained from these efforts play an important role in the process of informed decision-making [9], these skills could be considered to be important components for citizenship. Statistics education can contribute to developing these abilities. Still, more research on the implications of technological innovations on the teaching and learning of statistics is needed involving teachers and experts to conceptualize broadly accepted statistics education preparing for the digital age.

3 Advancing progressions: Technology and data visualization in statistics education

Gal [16] identifies statistical literacy as a key ability for people in our data driven society and underlines the importance of statistical literacy for citizenship. Graphical representations are more likely to facilitate intuitive access to vast data sets than numbers itself do [14] and are, therefore, the most common data information sources facilitating data understanding and providing support for making decisions under uncertain circumstances [44, 45]. Visual thinking and dealing with visual information are among the most powerful capacities of human minds [2] opening possibilities to provide information with meaning. The skill of the human brain to distinguish shapes, colours, sizes and structures at one time and, furthermore, to complement partly missing information is necessary when visualizing various aspects of data as graphical representations of information on complex phenomena [16]. We should consider statistical literacy as an ability of translating graphical representations into meaningful statements by the use of mathematical and statistical knowledge. The more facets of information given through different qualities of graphical representations, the more complex is the process of providing data with meaning and the more skills are needed [16]. Thus, various types and the diversity of data also demand new ways of structuring, organizing, visualizing data and analysing these visualizations. We conclude that common, often static visualization techniques like bar charts, boxplots or distributions for single variables do not meet the requirements of the multivariate nature of data. Suitable visualization methods and tools used therefore have to be multidimensional and dynamic [3], to intuitively explore more facets of the investigated phenomenon behind data.

New technological possibilities for statistically analysing large sets of data by visualizing them have just been discovered for school statistics education. Educational frameworks responding to these developments are rarely found, but they do exist. For example, Prodromou [34] defines a particular framework for visual analysis in statistics education with Open Data. After identifying the task, and with strong interaction between all the stages, they cover a) foraging for data, b) the search for visual structures, c) finding insights about important aspects therein and, finally, d) acting in the means of accepting the result of the visual analysis, improving the analysis on any stage or varying the identified task. Garfield and Ben-Zvi [18] provide an extensive overview of research studies concerning technology to improve student learning of statistics often by the use of graphical representations of data as well as they give recommendations and examples to foster students' statistical reasoning addressing the big ideas of statistics by visual methods. Distributions may be recognized by their shapes, the centre by, for instance, identifying symmetries or peaks, variability by the extension of the visualized data set, and groups may be compared using these characteristic properties.

Besides diverse studies concerning the didactics of technology integration in school statistics education, plenty of tool analysis focusing on technology can be found in literature, e.g., [18, 3]. These studies show that statistics education strongly requires a well-reasoned application of technological tools [24]. The most common tools, which many authors refer to, are TinkerPlots presented by Konold and Miller [22] and Fathom presented by Finzer et al. [13]. While educational research is usually concerned with the use of smaller data sets, there are some few studies on tools for statistics education that focus on the use of Big Data or, respectively, the use of Open Data in education, e.g., [36, 46]. However, as delineated before, demands of the data society are not completely be covered by understanding the qualities of small data sets or sets of simulated data. Therefore, studies concerned with Open Data taking the example of the software Gapminder will be emphasized here. Moreover, with a broader view on the topic we will depict further technological possibilities to access statistics education, below.

Introducing the Gapminder software [41] that includes numerous datasets concerned with society and economy, worldwide, Hans Rosling was a pioneer in visualizing Open Data for educational purposes. The data base of Gapminder contains data from all statistical bureaus, worldwide, beginning in the 19$^{\text{th}}$ century. For instance, the vast data base includes data on health, education, economy, energy, infrastructure, environment, and more. It was recently extended by a connected data base of photos called Dollar Street which shows photos of the living circumstances of people, worldwide, depending on their income. Moreover, the Gapminder Foundation elaborated various projects and plenty of teaching materials to identify and to reduce devastating misconceptions [40] about global development. The software, the materials and all data are freely available. Besides visualizing data there is no further possibility for statistical calculations. However, the data provided on the Gapminder's homepage can be downloaded for further calculations with other tools, e.g., with GeoGebra, Excel, or SPSS.

Figure 1 shows an exemplary bubble chart as a time series animation of the two variables Income (GDP/capita inflation adjusted) and the Human Development Index (HDI) which is influenced by lifespan, education, and economy. Colours show the region of countries and bubbles size stands for population size. Clicking on a bubble in the animation, the name of the country and exact values of the variables are displayed, also a track of the marked bubble is given during the animation. There are five other types of ready-made presentations, graphics on income distribution, trends, ranks, ages, and diagrams illustrating data in a map. In particular, the bubble chart meets the demands of visualizing

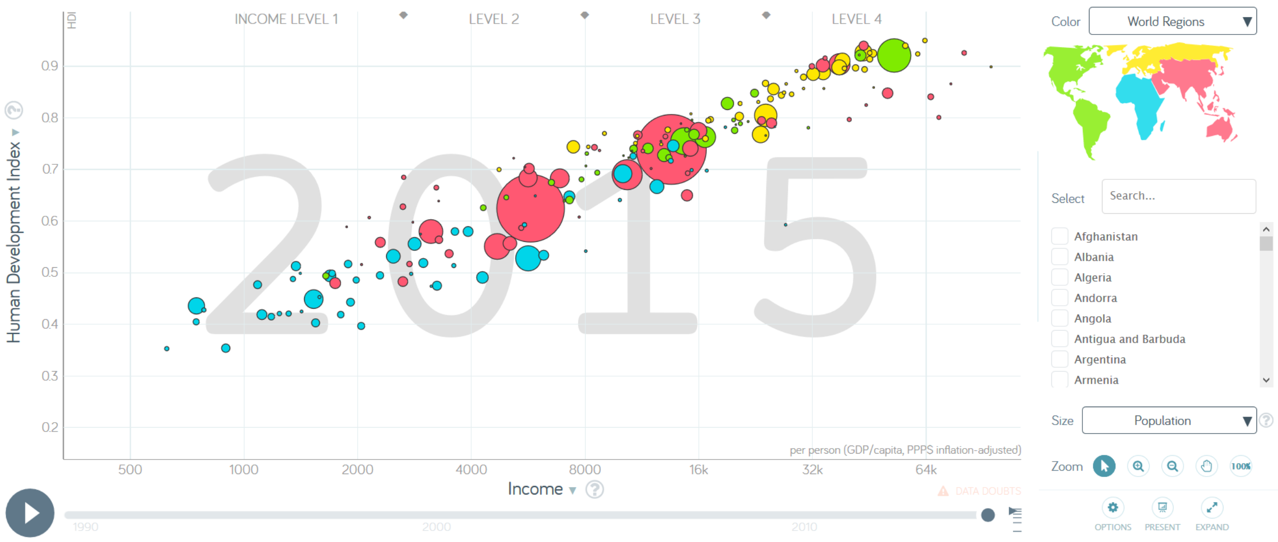

Figure 1: Bubble chart of Human Development Index dependent on the income in 2015 visualized by the Gapminder software

multivariate data, as the five variables income, HDI, population size, region, and time are represented in the animated graphic.

Until today, broad research on the use of this software in statistics education is missing, although, all research projects presented here, show various opportunities, promising results, and chances for further development. Prodromou [34] presented a study addressing students' informal inferential reasoning by the use of Gapminder. Students aged 14 to 16 were asked to argue for a country to live and work in the future by exploring various data on countries using the Gapminder tools. The results of the study show developments of students' inferential reasoning from informal to formal by constructing actively some of the big ideas of statistics [18] as to centre, distribution or comparing groups. Figure 1 shows a possible graph of this investigation. In a second study [35] adults' perception of risk was examined when identifying hazardous events by exploring appropriate data sets in Gapminder. Besides a focus on the research questions of risk perception, the results show that adults, with no extensive background regarding mathematics or statistics, were able to intuitively use the software for their investigation. Another example of using Gapminder for an introductory statistics course [25] emphasizes the important role of real-life data. Taking these studies together, real-life data with social relevance that personally affects students obviously have an influence on the commitment to explore these data sets. Cimpoeru [7] gives a further analysis of the Gapminder tool regarding benefits and possible drawbacks, such as overestimating the average regarding the spread of values and the lack of distribution inside countries. These results may help to further develop the software and to conceptualize future studies concerning the software Gapminder. Just recently, based upon these prior studies, the authors of this article conducted and implemented a research study addressing students' intuitions of the big ideas of statistics when following the cycle of inquiry and visual analysis [34] by the use of Gapminder. Figure 2 shows an example of the applied teaching materials provided by the Gapminder Foundation.

Students aged 14 to 15 participated in a project to find out more about poverty in the world. Using various worksheets, students investigated the phenomenon by exploring related variables. These

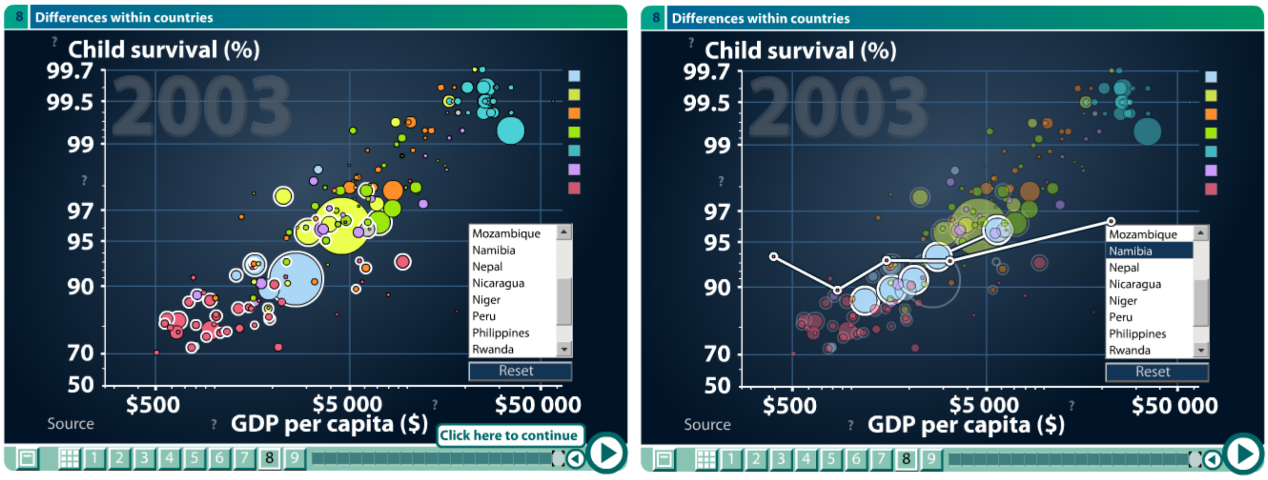

Figure 2: Gapminder's teaching material displaying variables of income and health

worksheets were analysed regarding intuitive approaches to diverse statistical concepts. The initial results of the study indicate that some of these concepts, such as models of regression, or the ideas of correlation, centre, spread and variability, seem to be intuitively accessible for students, whereas the idea of distribution apparently calls for a more extensive development. In addition, various opportunities to address further statistical abilities were detected, such as fostering students' statistical literacy in the age of Open Data [37], reasoning about measurements and collecting data or illustrating the findings.

Beyond traditional boundaries of statistics education, data visualization could also be concerned with more general ways of displaying information. Therefore, the process of visualizing data should go beyond statistical graphical representations. Many authors argue, as well, that making real data meaningful [8], communication of statistical findings [17] and statistical storytelling [42] are important skills to be taught in statistics education. For instance, information images or infographics (see figure 3) as visual representations of information, can be used in education for developing information modelling skills by exploring, systemizing and summarizing information about the investigated phenomenon. Some studies and meta-studies, e.g., [20], show positive effects on learning and teaching processes assisted by infographics such as articulating data-driven insights, developing analytical thinking skills or retaining facts in memory for a longer period of time. Numerous tools to build infographics can be found online, but we have found no research on these tools for the use in statistics education. Interested readers might look further at Taspolat et al. [43], which provide an informative overview regarding the educational matters of the topic, summarizing research studies on the learning processes supported by infographics.

Another way of quantitatively analysing and visualizing qualitative data is creating word clouds. After inserting a text, algorithms based, e.g., on frequency, distance or correlation analysis, create a cloud of words with varied sizes as graphical representation for the frequency and different location and colours as graphical representation of distance and correlation. As an example, figure 3 shows the word cloud of a draft of this article with around 4.000 words created by the open source web-application WordItOut; some words, like "et al.", were filtered out manually.

In this section we have pointed out that visualization is essentially for making data meaningful.

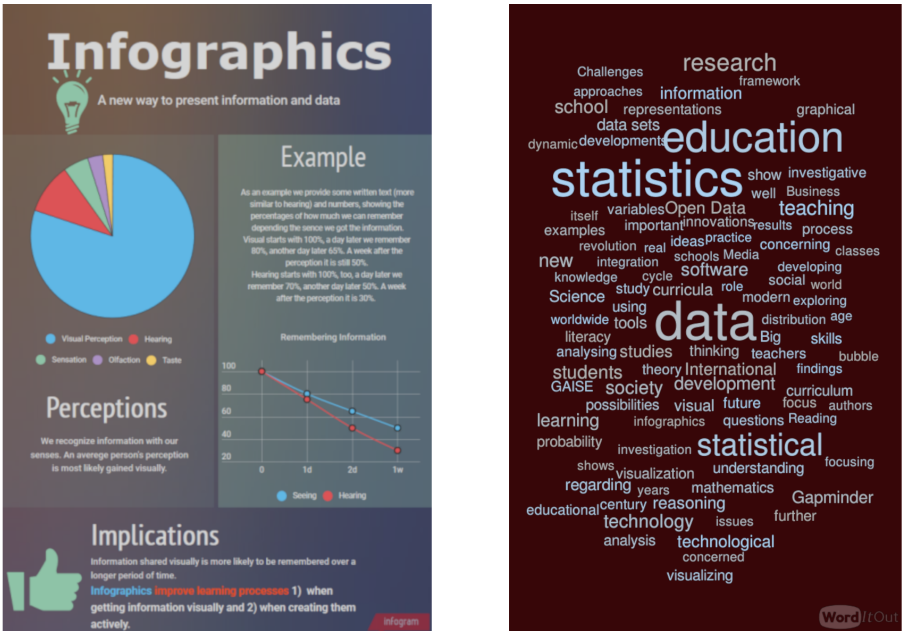

Figure 3: Infographic on visual perceptions and word cloud of the draft of this article

The framework for visual analysis of data [34] combined with frameworks for statistical problem solving, e.g., [15], and for statistical literacy [16] in the age of Open Data [37] establish constructive directions for data-rich statistics education. Research studies and best-practice examples show many prospective opportunities of deepening statistical skills by establishing new types of data visualisations to provide data with meaning.

4 Conclusion: Rethinking statistics education

According to our analysis, most curricula, worldwide, split up the statistical investigative cycle [47] over the school years. Statistics education in earlier grades concentrates on the process of asking statistical questions, gathering data and reasoning on the nature of data. In contrast, the focus in higher grades emphasizes the analyses of data in terms of calculation techniques and inferential reasoning. Splitting up these skills apparently lays a basis for not using real data in classrooms in order to avoid too extensive investigations in classes [38]. This situation is a contradiction to the recommendations of many authors who are emphasizing the value of real-world data, the role of its contexts and its importance to follow the investigative cycle. Paying attention to these matters, best practice examples have shown that students are often strongly engaged in the learning process and due to the use of technology even very young students are capable to construct big ideas of statistics by themselves, years before curricula require it [34, 46].

We also described that the rapid change in technological advances, as it has happened during the decade, poses a profound and constant challenge to society as a whole [30]. Not only issues regarding technical innovation itself should be considered, but also ethical questions or privacy issues arising with this development and these should be integrated in education as well. Therefore, curricula must catch up with technological innovations and the obligations arising for the education of future generations [38]. As several studies show, teachers are having major problems with the understanding of statistics and its teaching [18]. Thus, researchers recommend focussing on pre- and in-service teacher education in data-based statistics to change the way statistics is taught in schools [32].

Several examples of the successful integration of new technologies in school education demonstrate that new horizons in statistics education regarding the visual exploration of real-world data also open new possibilities for a deeper understanding of society, e.g., [46]. Therefore, educational statistical tools must be able to handle large sets of real data with strong, dynamic capacities [3] in order to explore these data sets graphically [34]. An easy integration of various, easily accessible data sets concerning society, economy, environment, and other global phenomena [41], could also induce a regular use of Open Data in mathematics and science classes. Isolated statistics classes could be changed into part of an interdisciplinary subject, like Watson [46] recommends, focusing on the statistical investigative cycle [1] in each Grade with a strong focus on data itself, including privacy and ethical issues or the quality of data.

Although acknowledged institutions like the OECD or the IASE promote a broad approach to statistics education, as well as several research studies indicating that using technology for analysing real-world data graphically is beneficial for students' development of various statistical ideas, important questions on conceptualizing modern statistics education are not yet answered. Regarding the broad field of statistics, we do not yet know enough about the knowledge, skills and competencies students should have to be able to responsibly participate in the data society and how statistics education can contribute effectively to arbitrating these.

As Perez [30] recommended the building of a framework for the best social use of modern technology and, moreover, statistics is playing in nearly every science backyard, everyone being involved in statistics education is challenged to contribute to a beneficial development of data society in the digital age. Therefore, we should rethink the picture of statistics as science of calculations fostering innovative approaches in visualizing data as well as illustrating and communicating the findings. In times of ambiguous information, data education is even more important and the use of real-world data on topics concerning society may contribute to spread a more rational, fact-based view of the world.

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