

Breaking the Curse of Visual Data Exploration: Improving Analyses by Building Bridges between Data World and Real World

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Abstract: Visual data exploration is a useful means to extract relevant information from large sets of data. The visual analytics pipeline processes data recorded from the real world to extract knowledge from gathered data. Subsequently, the resulting knowledge is associated with the real world and applied to it. However, the considered data for the analysis is usually only a small fraction of the actual real-world data and lacks above all in context information. It can easily happen that crucial context information is disregarded, leading to false conclusions about the real world. Therefore, conclusions and reasoning based on the analysis of this data pertain to the world represented by the data, and may not be valid for the real world. The purpose of this paper is to raise awareness of this discrepancy between the data world and the real world which has a high impact on the validity of analysis results in the real world. We propose two strategies which help to identify and remove specific differences between the data world and the real world. The usefulness and applicability of our strategies are demonstrated via several use cases.

1 INTRODUCTION

Nowadays, large amounts of data are generated and collected within mere seconds. As a result, constantly increasing amounts of information are available and subject to an increasing number of analytical data acquisitions and new technological possibilities with regard to gathering, storing and distributing data. Many people are interested in gaining knowledge from this data, for example, by using data mining algorithms or visual analytics (Keim et al., 2008) methods. Afterwards, the generated knowledge is applied on the real world where the used data originate from. However, there is a flaw inherent in our everyday analytical reasoning: The collected data is no perfect representation of the real world. Many facets of our surroundings cannot be measured with the necessary precision, if at all. Also, there likely exist factors influencing the analysis that we are not yet aware of and therefore do not measure. Since performing an analysis on incomplete and noisy data cannot lead to fully complete and correct results, we claim that *data is always wrong* to some extent. Consequently, the analysis might not generate valid real-world knowledge, but instead knowledge that is valid in the world represented by the data. For example, when measuring the speed of cars in a rally race, the collected data is necessarily rounded to a certain degree. Also additional factors, such as vertical

accelerations might be neglected. Therefore, results of the analysis based on this data, such as the maximum speed or the average acceleration of cars, only deliver answers to the abstracted data on the rally race, not the rally race itself.

In this paper, we draw attention to this important problem to which we further refer to as *the curse of visual data exploration*. Without a doubt, for some domains and tasks, the considered data can be sufficient to lead to similar results as if the entire real world would have been taken into account for the respective analysis. Still, each diversion in the data from the real world leads to a slightly less optimal result, and it is often hard to tell how much the data diverts from the real world. This issue has already been recognized and been part of researcher discussions all around the world, e.g., in the panel discussion of the 2017 IEEE Symposium on Visualization in Data Science (VDS). The related topic of uncertainty analysis is mainly concerned with the data gathering process and the validation of gathered data. Often, however, the problem does not lay in the data itself (e.g., faulty or missing data), but in the scope of the measured data (e.g., parameters not considered for analysis), which is usually not addressed by uncertainty analysis.

To raise awareness and foster discussion, we examine the *curse of visual data exploration* (Sect. 3) and provide possible strategies to *break the curse* (Sect. 4)

by focusing on projecting data and analysis results back into a more comprehensive real-world context. If the real world is not sufficiently described by our data, we are able to identify this by inspecting the resulting visualizations in the overall context of the real world and evaluate if all necessary data is considered in the analysis. We elaborate on the general usefulness of our proposed strategies and provide several examples of projects (Sect. 5) in which we applied our proposed recommendations, even though they cannot yet be applied to every analytical use case (Sect. 6).

2 RELATED WORK

To identify the *curse of visual data exploration*, we studied published Visual Analytics pipelines in the literature and recognized a missing connection between the generated knowledge and the real world. Through all stages, different sources modify the data in a way that the data no longer fully corresponds to the real world. We first discuss related work in uncertainty analysis (Sect. 2.1) followed by an overview about data validation (Sect. 2.2). We position our work within the aforementioned works in Sect. 2.3.

2.1 Uncertainty

As uncertainty occurs in almost every field of research, one important challenge is to find a generalized definition of uncertainty that can be applied to various domains. MacEachren et al. (MacEachren et al., 2005) recognized early on that uncertainty is a complex concept which needs to be subdivided into different components. Subsequently, suitable methods for the representation and processing of uncertainty are needed. Skeels et al. (Skeels et al., 2010) surveyed the state-of-the-art and introduced a model identifying components of uncertainty in various fields of research such as information visualization. Their model divides uncertainty into three levels with increasing abstraction. *Measurement precision*, *completeness*, and *inferences*. Measurement precision deals with imprecise measurements of sensors which could be identified by confidence intervals. One level above is the completeness which describes the loss of information by using projections or sampling techniques. The highest abstraction reflects the inferences. Inferences describe the uncertainty of predictions of future values based on current data. Here, one challenge is that prediction models cannot predict a value if the underlying data has no similar data points. All levels are covered by an additional component (*Credibility*) which describes the trustfulness of the data source as well as potential

disagreements when comparing among other sources. Gershon et al. (Gershon, 1998) describes the challenges of visualizations in an *imperfect world*. In their taxonomy, they illustrate and summarize the different challenges that arise when gathering data from the real world. The resulting taxonomy is divided into two parts, on the one hand, the imperfection (uncertainty) during data acquisition. On the other hand, falsely represented data, for example, an overplotted visualizations or the use of an inappropriate device.

2.2 Data Validation in Visual Analytics

Several definitions of data validation exist in different domains, e.g., in the Unece glossary in statistical data editing (UNDP, 2018) it is described as an action to verify if a value matches an allowed set of values. Also, Wills and Roecker (Wills and Roecker, 2017) describe data validation as the ability of a model to detect variance in the data including, for example, the recognition of missing values and outliers. Over the years, a variety of outlier detection techniques such as anomaly detection (Chandola et al., 2009), noise detection (Rehm et al., 2007) or novelty detection in time series (Dasgupta and Forrest, 1996) have been proposed. Hodge and Austin discuss several outlier detection techniques in their survey (Hodge and Austin, 2004) and identify three types of how outliers can be found based on different knowledge about the data. In the first type, there is no knowledge about which data points belong to the outliers. Consequently, outlier detection is based on a statistical distribution to classify whether a point belongs to a specific distribution or not. For the second type, each data point requires a label to indicate whether it is an outlier or not. Subsequent, classifiers are trained by using these labels to predict if a new data point is an outlier or not. This involves the generation of a classifier for detecting normal data points and abnormal data points. Type three again uses pre-labeled data like in type two with the difference that these classifiers trained only on the data points which do not belong to the outlier class. This can be used to determine whether a new data point belongs to the set of valid data points based on the training dataset. However, data points which do not belong to this set are not necessarily outliers. This approach for type three is similar to algorithms for semi-supervised recognition or detection tasks.

2.3 Positioning of our Work

Approaches handling data manipulation, for example, in a visual analytics workflow are mainly concerned about stages between data collection and knowledge

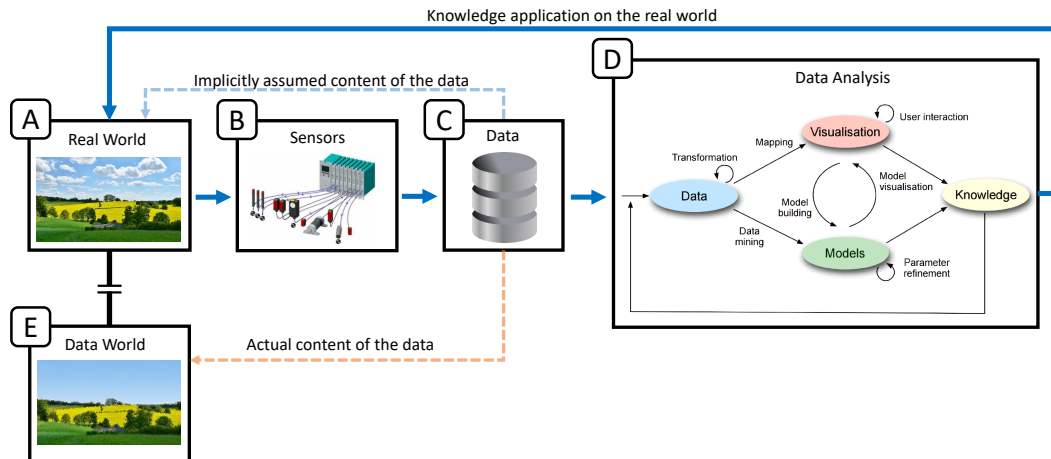


Figure 1: The *curse of visual data exploration* displayed in an extended visual analytics model. In common data analytics tasks, the procedure starts in the real world (A) where information is collected using sensor technology (B) and stored (C). Afterward, the gathered data is analyzed as described in various proposed visual analytics models. This process is here depicted in (D) at the example of the Visual Analytics pipeline by Keim et al. (Keim et al., 2010). The knowledge generated by these models is often assumed to be correct in the real world implying that the gathered data represents a complete and correct copy of the real world. However, as the gathered data only contains a subset of aspects (the data world (E)) that can have an influence on the analysis process, the generated knowledge may not be complete or even invalid in the real world.

generation. Our model differentiates from the current state-of-the-art by introducing a new validation step enabling the validation of whether extracted knowledge applies to the real world.

3 THE CURSE OF VISUAL DATA EXPLORATION

“The cost of bad data is the illusion of knowledge” (Tunguz, 2018). At the beginning of the data analysis process it is important to consider the quality of the collected data. Research nowadays is mainly concerned with improving the results of an analysis, both regarding performance and quality. Unfortunately, the quality of the data used for this analysis is often not ensured to be adequate for a given task. If the quality of the data lacks in detail, is faulty or incomplete, conclusions drawn from the analysis might only be referable to the data but not to the actual real world the data was taken from. Therefore, generated knowledge would probably not apply to the investigated research question as intended.

A broader framework for common analytical workflows such as visual analytics can be seen in Fig. 1. The collection of data is the starting point where data is obtained from the real world (Fig. 1 A) using, for example, sensor technology (Fig. 1 B). We refer to the real world as the world we want to analyze. Usually, this is the physical world around us, but it could also be a conceptual world like a stock market. Sensors capture properties and discretize continuous signals to

digitalize real-world information (e.g., video recordings). There are various types of sensors, for instance, thermometers, pressure sensors or cameras. Gathered data is merged and stored digitally as discrete values, abstracted to bits and bytes (Fig. 1 C). Stored data is typically the starting point for common analytical workflows such as visual analytics (Wang et al., 2016).

In Fig. 1 D, we inserted the Visual Data-Exploration Pipeline by Keim et al. (Keim et al., 2008) as an example for arbitrary visual analytics pipelines. Any other analytical workflow might be inserted here as long as the following two conditions are met:

1. They start with digital data as basis for the analysis.
2. Their goal is to generate knowledge about the real world (basis from which the data was collected).

Finally, the output of the analysis (knowledge) is attributed back to the real world from which the data was extracted from. The generated knowledge is naturally assumed to be valid in the real world since all the input data came from the real world. In Fig. 1, this assumption is depicted by a blue arrow going from the extracted knowledge to the real world. The fact that knowledge is valid in the data world does not mean that it is not valid in the real world as well. Some information from the real world is more important to the analysis than other, and usually, most of the real world information is not relevant for a given analysis task. Therefore, the validity of the knowledge in the real world strongly depends on how accurate and complete all important information sources have been measured. In some cases, analysts might be aware of

missing aspects in the data that are hard or even impossible to capture. However, in general, the real world is a complex construct that is impossible to capture completely and correctly. Due to this fact, analysts have to assume that the data world and the real world are similar enough to transfer generated knowledge to the real world. This is what we call the *curse of visual data exploration*.

In detail, we refer to the *curse of visual data exploration* as the natural condition of incomplete or faulty data as a basis for analytical workflows, leading to a wrong association of generated knowledge to the real world. This association of knowledge would only be legitimate if the gathered data would completely, correctly and exclusively represent the real world. However, knowledge would also be transferable, if the data used for the analysis contains all information influencing generated knowledge. I.e., in practice it would be sufficient if all analysis relevant information would have been considered throughout the analysis. Factors that do not influence the analysis results (irrelevant real-world data) can be neglected. Whenever data is collected, there is a high chance that some important information is neglected that would impact the analysis process and therefore the generated knowledge. This loss of important real-world information can occur in several ways. Sensors may produce systematic or random errors, sample insufficiently or create somewhat unwanted biases in the data. Besides, the analyst may not be aware of factors that are not yet considered in the analysis (missing sensors). In statistics, such factors are also referred to as *lurking variables* (Brase and Brase, 2011). Faulty data could also be introduced through abstracting procedures during the gathering process (e.g., aggregating, binning, sampling, digitalizing, discretizing). These complications throughout the gathering process lead to a discrepancy between the real world and the collected data. The world described by the data is, therefore, not perfectly representative of the real world (faulty, incomplete). In the following, we refer to the entirety of the gathered data as the *data world* (Fig. 1 E). The analysis is conducted in the data world and, therefore, it is only ensured that generated knowledge is valid in the data world.

4 BREAKING THE CURSE

In this section, we propose two strategies that aim at minimizing the chance to be affected by the *curse of visual data exploration*. The goal of these strategies is to make sure that the generated knowledge is not only valid in the data world but also in the real world. Both strategies follow the same principle of going back to

the real world to validate the data or the results.

To break the curse, we aim to minimize or remove the gap between the real world and the data world. Since the analysis results are valid for the data world, they would also be valid in the real world if both are equal to each other. More precisely, it would be enough if both worlds were equal concerning all information that affects the analysis as the results would then be the same. In the following, we refer to this information as *analysis relevant information*.

Since the data world cannot realistically be an exact copy of the real world, the data world usually contains a subset of the information available in the real world. To ensure a valid analysis procedure and to allow inference of results to the real world scenario, the following conditions have to be true:

- S1** Information contained in the data world is correct, i.e., it is not contradicting to real-world data.
- S2** Dimensions (attributes) contained in the data world are also present in the real world, i.e., the data world is a subset of real world.
- S3** Dimensions contained in the data world cover all the analysis relevant information of the real world.

In general, it is impossible to guarantee that all conditions (**S1-S3**) are fulfilled, e.g., due to imperfect measurement accuracy or the deployment of derived dimensions (artificial dimensions that do not directly reflect properties of the real world). However, it is desirable to optimize **S1**, **S2** and **S3** as much as possible.

S1 ensures that the collected data is correct and therefore not negatively impacting the analysis. Common causes for violations against **S1** are random or systematic errors in measurement devices. **S1** can be ensured by comparing each value present in the data world with its corresponding value in the real world. This procedure can be time-consuming if the data set is sufficiently large and sometimes even impossible if the measurement cannot be repeated. **S2** ensures that no additional data exists in the data world that does not describe the real world. This could happen if the dataset is a composition of multiple sources of which some are valid sources describing the real world and others are not. Validating **S2** can be done by checking if every individual dimension of the data world can be found in the real world. **S3** ensures that no analysis relevant data is missing. If analysis relevant data would be missing, the analysis can end up at faulty results as crucial information would have been neglected for the examination of the real world. Usually, the examined real world is complex, hampering the validation process and making automatic validation impossible. Therefore, user involvement is required. An analyst can apply their real-world knowledge to

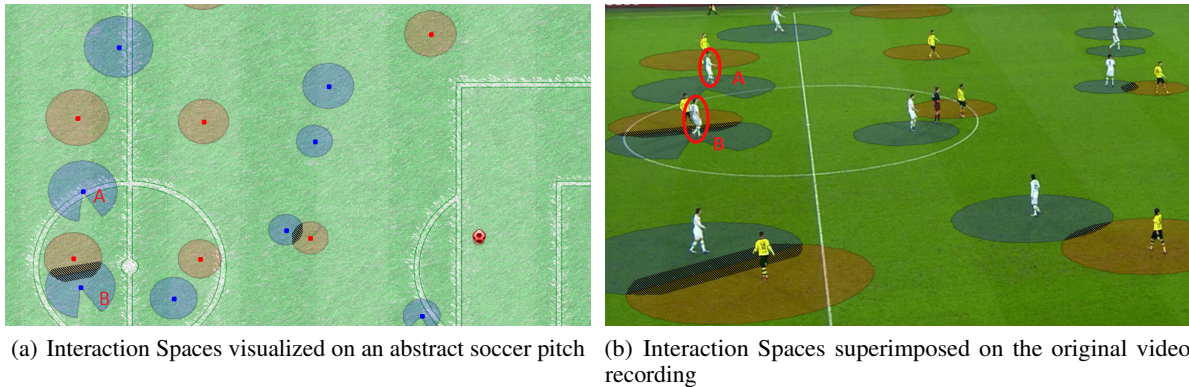


Figure 2: Calculating interaction spaces for the same scene in a soccer match once visualized on an abstracted soccer pitch (left) and once superimposed on the original video recording (right). Interaction spaces are used to calculate the region each player is able to control until the ball reaches him or her, therefore, a player’s orientation is important during calculation. The available data consists of x - and y -coordinates for each player. In this scene, the annotated players **A** and **B** are moving upwards which influences their respective interaction spaces. By projecting the same visualization into the original video recording (right), we notice that the players are not running forwards, but sideways which is currently not captured by the data gathering process. Figure 2 (b) is extracted from a television match recording from the German Bundesliga being broadcasted on the Sky Sport TV channel operated by Sky UK Telecommunications (Sky, 2018) and enhanced by the superimposed interaction spaces.

identify dimensions that likely influence the current analysis task. For example, if the task is to predict crop growth, the analyst would likely identify dimensions like solar radiation and rainfall as important. However, it is challenging to recall all possible variables influencing a process, especially if the analyst is not reminded of their existence in some way. This makes **S3** the hardest of the statements to verify. In the following, we propose two exemplary strategies to verify **S1-S3** with the aid of visualization. Currently, our strategies are limited to suited data and use-cases. For example, very abstract data such as multivariate results of questionnaires might not be optimal for the presented approaches as they have no spatial, temporal, volume or similar context that could be visualized easily.

4.1 Reconstructing the Real World

Since validating **S1-S3** can be rather complex and time-consuming, we propose a strategy for how their validity can be checked using visualization. During the analysis step, complex information is often abstracted and visualized making it easier to comprehend. We propose a similar strategy to check the validity of **S1-S3**. While we usually collect data from the real world and create data representations, it is also possible to go the other way around and use the data contained in the data world to reconstruct a subset of the real world.

If **S1-S3** hold true, this recreation should contain each aspect of the real world that is thought to be relevant for the analysis process. Comparing the visual representation of the reconstruction to the real world can help to reveal differences between the two such as missing or faulty properties. The visual representa-

tion should aid the user in spotting differences which would be hard to notice by just looking at the abstract data. With the aid of this reconstruction, the user can make use of knowledge about the real world to check the validity of **S1-S3** by checking the reconstruction for inconsistencies or the absence of analysis relevant information. If there is anything in the reconstruction which is not present in the real world or differs from it, then either **S1** or **S2** is violated. Since visual representations help to understand a large amount of information quickly, this process is assumed to be a lot more efficient than validating every value in the data against its real-world counterpart as described earlier. Still, identifiable missing data can be of even higher interest. For instance, sports analysts examining soccer matches are interested in analyzing regions their players can control (Interaction spaces (Stein et al., 2016); see Figure 2). The orientation of players is an important factor in calculating these interaction spaces, as players need to turn around to control the ball if it is behind them. This takes time and, therefore, decreases the area they can control behind them. Accordingly, when an analyst annotates the interaction space of a player manually while watching a video stream of a soccer match, the shown orientation of the players is subconsciously used in the analysts mental model. Consequently, if the company collecting the data does not include the information about player orientation in the computer-assisted data gathering and analysis process **S3** is violated. Looking just at the data as single x - and y -coordinates as it is saved in the database, it is hard to realize that this attribute is missing. At this point, the reconstruction of the real world could improve the analysis process. In a three dimensional

reconstruction based on the collected data, players have no eyes or other indication of their orientation on the soccer field. Additionally, players would never be running back- or sideways. We assume that analysts realize that this data is missing since their mental model is not confirming the missing input. After identifying a dimension that is missing in the data world (in this example, player orientation), the respective data can be added to repeat the whole process until no more flaws are discovered.

4.2 Projecting Results Back into the Real World

Our second proposed strategy does not aim to validate the data world directly but instead confirms analysis results by projecting them back into the real world. In analytical workflows such as visual analytics, generated knowledge is often presented via abstract visualizations like parallel coordinates (Inselberg and Dimsdale, 1987) or glyph visualizations (Fuchs et al., 2017; Wickham et al., 2012). These visualizations are useful to explain analysis results to humans, but they often include little context information about the real world. This creates a gap between the data world and the real world, even though the goal is usually to connect the generated knowledge to the real world. This separation makes it hard to judge whether the analysis results fit into the context of the real world. We argue that by projecting the analysis results into a space that is closer to the real world, users are enabled to reveal contradictions that would go unnoticed otherwise. Afterward, it must be ensured that the identified aspects are included in the data (S3) as well as measured correctly (S1). This proposed strategy has the additional advantage that problems within the analysis itself can also be spotted.

Going back to the previously introduced soccer example, automatically determined interaction spaces of players are calculated based on players' speed, distance to the ball and running direction. Afterward, interaction spaces are visualized as circles or circular sectors on an abstracted soccer pitch as can be seen in Fig. 2 (a). However, a player's movement direction does not necessarily reflect his or her body orientation. If the same visualization is projected into a video of the real world soccer match, as shown in Fig. 2 (b), it has reportedly been easier to spot that there is a problem with the used data for this analysis. In several expert studies performed in recent work (Stein et al., 2018), several invited soccer analysts repeatedly reported that "[...] they became more aware of a visualization's limitations and possibilities for improvement in the future. As, for example, soccer players were not repre-

sented by moving dots on an abstract pitch anymore but with the real persons, the experts noticed that the body pose is currently not always reflected correctly in the calculation of interaction spaces. If a player is running forwards or backwards, the resulting interaction spaces are identical. This exemplary problem could not attract attention outside of the video visualization as no data about the body poses are collected." (quoting (Stein et al., 2018))

5 USE CASES

To demonstrate the applicability of either reconstructing the real world (Sect. 4.1) or projecting the results into the real world (Sect. 4.2), we present a detailed use case for each of them. By the example of collective behavior analysis, we show how the data world can be reconstructed and verified. Afterward, we consider the use case of a criminal investigation, showing how the extracted analysis results can be projected back into the real world to verify the data basis for the analysis.

5.1 Collective Behavior

The first use case deals with the calculation of thermal spirals from tracked bird movement data. For this purpose, students from the University of Konstanz reconstructed a part of the real world based on the available data to validate if some features are missing as described in Sect. 4.1. The movement data of the birds are provided by an online database called Movebank (Wikelski and Kays, 2014) managed by the Max Planck Institute for Ornithology (MaxPlanck, 2018). Each bird is equipped with a GPS receiver to record the current position, direction and altitude. Researchers use this data to identify characteristics to see whether individual birds communicate to the swarm where thermal spirals are located. The integration of satellite images and elevation data into the virtual environment helps to investigate the external influences of thermal spirals better. During the analysis, the experts noticed that individual birds moved away a few meters from the swarm within a second. In the beginning, it could not be explained why the birds behave this way and how this influences the collective behavior. After integrating weather data as another data source into the virtual world, they noticed that a gust of wind has caught the birds and dragged them a few meters. This was only possible by representing the wind with the help of cloud movements. Seeing the clouds move in the same direction as the birds made it easier for the analyst to create this connection as compared to just looking at the numbers in the dataset. In Fig. 3,



Figure 3: The GPS coordinates of tracked birds were projected into a virtual environment to analyze their behavior in a thermal spiral. From the eyes of a bird, you can see how other birds use the thermal spiral to move upwards in a circle. Also, the data is enriched by providing the surrounding landscape to recognize further factors which influence the behavior of birds. Using this visualization, it was possible to detect that specific winds, represented by cloud movement, could be responsible for a certain pattern in bird movement, which was previously not explainable.

you can see a part of the virtual environment out of the eyes of a bird. The current satellite image which matches the GPS position of the bird is located at the bottom so that users can always see the exact surroundings. This includes information like the height of the mountains as well as the land usages. The reason for displaying satellite images and elevation data is that thermal spirals behave differently, whether they occur over mountains or flat areas. The projection into a simulation enables experts to recognize missing features like the weather information.

5.2 Criminal Investigation

When investigating a crime scene, context information is undoubtedly crucial. Many side factors are overseen if only considering the fraction of the real-world data that is at first glance the most important data. For example, during a rampage in a city, the data available to law enforcement agents could consist of video material of surveillance cameras or pedestrians, mobile cell connections as well as email conversations of the suspects, reports of eyewitnesses, GPS locations of the suspects and much more. Still, it is impossible to consider all data available. Many dimensions of the real

world that seem irrelevant would naturally have to be neglected to avoid processing overload (e.g., weather data, news data, traffic data or twitter data).

Algorithms might be able to extract features from video frames, analyze them and present condensed information to the analyst. This could, for instance, be achieved as follows: the algorithm searches in video frames for objects using deep neural networks and collects for each object all frames the object appears in. The result is a set of objects with corresponding trajectories of the objects. Subsequent visual analytic procedures could be deployed to analyze those trajectories. Knowledge deduced from this analysis is ascribed to the actual procedure of events throughout the incident.

Our strategy suggests projecting the extracted information back into the original footage. For instance, by marking matched objects in the video, or even by plotting the trajectories in a 3D reconstruction of the part of the city where the incident took place. This would create a geo-context that reflects the real world even more than video footage. Additional information such as weather or traffic information could be visualized as well. The original recordings could then be placed within this 3D world and be adjusted in time

and space. Investigators could then walk through the actual crime scene, navigate in space and time and view recordings of interest.

Hereby, faulty or missing data might become apparent quickly. Analysts might detect objects in the video footage that were not detected by the neural network or classified wrongly. For instance, two objects with trajectories running along next to each other which are separated by a river in between could have wrongly be identified as a group by the algorithm. The additional geo-context given in the 3D reconstruction makes this error visible. The analyst learns that the algorithm did not consider geo-characteristics for the grouping of objects and is able to adapt the algorithm or at least consider its impact on the interpretation of remaining results.

6 DISCUSSION

With our work, we want to rise awareness that the applicability of analysis results is highly dependent on the quality and completeness of the collected data. We discussed why collected data is not a perfect representation of the real world and introduced the concept of a data world in Fig. 1. We elaborated that the discrepancy between the data world and the real world can affect the validity of analysis results and called this problem *the curse of visual data exploration*. Two strategies were introduced which can reduce the extent at which this curse occurs. We consider our proposed strategies as a step towards more sophisticated solutions to detect invalid or missing data measurements by using the concept of bringing back the collected data and generated knowledge into the real world. Of course, this concept has its limitations. Projecting data into a visual space that is closer to the real world is challenging as each scenario has to be handled application specific. Some data may not have a straightforward representation in the real world at all, especially if data describe a concept that is not visible in the real world. By allowing the user to incorporate real-world knowledge, this concept allows to detect data problems or missing data that would otherwise be hard to find.

We present two strategies in our work, one which reconstructs the real world from the collected data (Sect. 4.1) and one which projects the generated knowledge back into the real world (Sect. 4.2). While the strategies are similar to each other, they can lead to different results. Reconstructing the real world from data can highlight data dimensions which are not present in the real world as described by **S2** in Sect. 4. For example, it could be that the data set has been manipulated by adding a dimension which does not exist in the real

world. Recreating the real world from this data would result in a representation of this additional dimension which is visible in the recreation. Using the visual representation of the reconstruction as well as real-world knowledge, it might be easier to spot this additional data compared to just looking at the data set. Finding these problems with the other strategy is harder, as the projection of the analysis results into the real world would not contain this additional dimension anymore. On the other hand, the reconstruction strategy cannot identify problems introduced by the analysis concept which can be found using the projection strategy. Whether one of the strategies is superior to the other in specific cases is subject to future research.

In general, our introduced model can be applied to other domains which focus on the extraction of knowledge from data. For example, the Knowledge Discovery in Databases pipeline from Fayyad et al. (Fayyad et al., 1996). In future work, we want to investigate how far back into the real world the knowledge should be projected to find most data quality problems. In the soccer example shown in Fig. 2, one could go back to images, to videos or even to a reproduction of the match with real players. Our assumption is that going back this far is counterproductive as it could make it too complex to project the data into the real world.

7 CONCLUSION

To overcome the illusion of knowledge generated by invalid or incomplete data, we extend current visual analytic pipelines with a validation step to detect data measurement errors (errors in the data world - i.e., in the data that is considered in the analysis). Our concepts are based on the idea that the extracted knowledge is projected to a representation of the real world to test if the knowledge fits to the real world. We discussed this generic problem and two exemplary specific solutions. It is notable that they are not generic and applicable for any kind of data.

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REFERENCES

- Brase, C. H. and Brase, C. P. (2011). *Understandable statistics: Concepts and methods*. Cengage Learning.
- Chandola, V., Banerjee, A., and Kumar, V. (2009). Anomaly detection: A survey. *AMC Computing Surveys (CSUR)*, 41(3):15.
- Dasgupta, D. and Forrest, S. (1996). Novelty detection in time series data using ideas from immunology. In *Proceedings of the International Conference on Intelligent Systems*, pages 82–87.
- Fayyad, U., Piatetsky-Shapiro, G., and Smyth, P. (1996). From data mining to knowledge discovery in databases. *AI Magazine*, 17(3):37.
- Fuchs, J., Isenberg, P., Bezerianos, A., and Keim, D. (2017). A systematic review of experimental studies on data glyphs. *IEEE Transactions on Visualization and Computer Graphics*, 23(7):1863–1879.
- Gershon, N. (1998). Visualization of an imperfect world. *IEEE Computer Graphics and Applications*, 18(4):43–45.
- Hodge, V. and Austin, J. (2004). A survey of outlier detection methodologies. *Artificial Intelligence Review*, 22(2):85–126.
- Inselberg, A. and Dimsdale, B. (1987). Parallel coordinates for visualizing multi-dimensional geometry. In *Computer Graphics 1987*, pages 25–44. Springer.
- Keim, D., Andrienko, G., Fekete, J.-D., Görg, C., Kohlhammer, J., and Melançon, G. (2008). Visual analytics: Definition, process, and challenges. In *Information Visualization*, pages 154–175. Springer.
- Keim, D., Kohlhammer, J., Ellis, G., and Mansmann, F. (2010). *Mastering The Information Age – Solving Problems with Visual Analytics*. Eurographics Association.
- MacEachren, A. M., Robinson, A., Hopper, S., Gardner, S., Murray, R., Gahegan, M., and Hetzler, E. (2005). Visualizing geospatial information uncertainty: What we know and what we need to know. *Cartography and Geographic Information Science*, 32(3):139–160.
- MaxPlanck (2018). Max Planck Institute for Ornithology. Movebank. <https://www.movebank.org/>. [Online; accessed 30-November-2018].
- Rehm, F., Klawonn, F., and Kruse, R. (2007). A novel approach to noise clustering for outlier detection. *Soft Computing*, 11(5):489–494.
- Skeels, M., Lee, B., Smith, G., and Robertson, G. G. (2010). Revealing uncertainty for information visualization. *Information Visualization*, 9(1):70–81.
- Sky (2018). Sky Go - Moenchengladbach vs Dortmund. <http://www.skygo.sky.de/>. [Online; accessed 30-November-2018].
- Stein, M., Janetzko, H., Breikreutz, T., Seebacher, D., Schreck, T., Grossniklaus, M., Couzin, I. D., and Keim, D. A. (2016). Director’s cut: Analysis and annotation of soccer matches. *IEEE Computer Graphics and Applications*, 36(5):50–60.
- Stein, M., Janetzko, H., Lamprecht, A., Breikreutz, T., Zimmermann, P., Goldlücke, B., Schreck, T., Andrienko, G., Grossniklaus, M., and Keim, D. A. (2018). Bring it to the pitch: Combining video and movement data to enhance team sport analysis. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):13–22.
- Tunguz, T. (2018). The Cost Of Bad Data Is The Illusion Of Knowledge. <http://tomtunguz.com/cost-of-bad-data-1-10-100/>. [Online; accessed 30-November-2018].
- UNDP (2018). United Nations Statistical Commission and Economic Commission for Europe glossary of terms on statistical data editing. https://webgate.ec.europa.eu/fpfis/mwikis/essvalidserv/images/3/37/UN_editing_glossary.pdf. [Online; accessed 30-November-2018].
- Wang, X.-M., Zhang, T.-Y., Ma, Y.-X., Xia, J., and Chen, W. (2016). A survey of visual analytic pipelines. *Journal of Computer Science and Technology*, 31(4):787–804.
- Wickham, H., Hofmann, H., Wickham, C., and Cook, D. (2012). Glyph-maps for visually exploring temporal patterns in climate data and models. *Environmetrics*, 23(5):382–393.
- Wikelski, M. and Kays, R. (2014). Movebank: archive, analysis and sharing of animal movement data. Hosted by the Max Planck Institute for Ornithology. *World Wide Web Electronic Publication*.
- Wills, S. and Roecker, S. (2017). Statistics for Soil Survey. http://ncss-tech.github.io/stats_for_soil_survey/chapters/9_uncertainty/Uncert_val.html#1_introduction. [Online; accessed 30-November-2018].