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Special Section on Uncertainty and Parameter Space Analysis in Visualization

Effects of visualizing uncertainty on decision-making in a target identification scenario

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ABSTRACT

This paper presents an empirical study that addresses the effects the visualization of uncertainty has on decision-making. We focus our investigations on an area where uncertainty plays an important role and the decision time is limited. For that, we selected an air defense scenario, where expert operators have a few minutes to make a well-informed decision based on uncertain sensor data regarding the identity of an object and where the consequences of a late or wrong decision are severe.

An approach for uncertainty visualization is proposed and tested using a prototype that supports the interactive analysis of multivariate spatio-temporal sensor data. The uncertainty visualization embeds the accuracy of the sensor data values using the thickness of the lines in the graphical representation of the sensor values. Semi-transparent filled circles represent the uncertain position, while a track quality value between 0 and 1 accounts for the quality of the estimated track for each target. Twenty-two experienced air traffic operators were divided into two groups (with and without uncertainty visualization) and carried out identification and prioritization tasks using the prototype. The results show that the group aided by visualizations of uncertainty needed significantly fewer attempts to make a final identification, and a significant difference between the groups when considering the identities and priorities assigned was observed (participants with uncertainty visualization selected higher priority values and more hostile and suspect identities). These results may show that experts put themselves in the "worst-case scenario" in the presence of uncertainty when safety is an issue. Additionally, the presentation of uncertainty neither increased the participants' expressed workload, nor the time needed to make a classification. However, the inclusion of the uncertainty information did not have a significant effect on the performance (true positives, false negatives and false positives) or the participants' expressed confidence in their decisions.

1. Introduction

Exploring, analyzing and making decisions based on vast amounts of data are complex tasks that are carried out on a daily basis. People, both in their business and private lives, walk the path from data to decision using diverse means of support. Decision support systems and software try to aid specialists to reach effective decisions, while handling large amounts of data. Since there could be errors in the acquisition of the data (measuring devices), processing phases (data mining techniques), performance reasons, or even in the graphical display of the information [1], some degree of uncertainty is almost always associated [2]. If visualization is used to communicate the content of the data or to explore it, the uncertainty needs to be included [3,4]. Moreover, the user should be aware of the nature and the degree of uncertainty of the displayed information, otherwise, there is a danger that data can be misinterpreted, potentially leading to inaccurate conclusions. For example, Andre and Cutler [5] found out that if uncertainties are not presented to operators, they tend to adopt risky behavior, and that operators have a tendency to ignore implicit or hidden decision criteria when they are not visually presented.

Current research regarding how to present uncertainties to support decision-making processes is very limited [4]. Even though the need for visualizing uncertainty associated with the data has now general acceptance [6], it is not easy to include additional uncertainty information into an existing visualization while maintaining comprehension [6,2]. There is a lack of empirical results indicating the effectiveness of the techniques in terms of how well they are perceived, understood and accepted by the users [7–9]. Moreover, an equally important question is how the visualization of uncertainty influences reasoning and decision-making within problem contexts for which uncertainty matters [10].

In this paper, we address this gap by reporting on the results of an empirical assessment that provide insights into how the visualization of uncertainty affects decision-making. We performed our

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investigations in an air defense setting, where the time for making a decision is limited, the cognitive load is, in general, high, and the consequences of a wrong decision are severe. Thus, we have selected an air defense scenario, where civilian and military air traffic operators have to control and monitor the air space analyzing dynamic, heterogeneous and uncertain sensor data.

Military and civil security personnel normally carry out tasks related to the recognition, identification and prioritization of the objects in an environment of interest (or surveyed area). The execution of these tasks is often challenging due to the need to synthesize large amounts of often disparate data into a meaningful whole as well as considering the prevalent political situation, time constraints, possible decision alternatives and their consequences. To perform the identification and prioritization tasks, it is important that the operators are able to understand the information collected, but also the qualifiers of this information (e.g., uncertainty). However, as stated by [11], it is not common that these systems incorporate such information qualifiers. This is further discussed by McGuirl and Sarter [12] who argue that support systems in general often present the operators with a diagnosis or solution to a problem with little or no explanation or qualification, which places the operators in a position where they must fully accept the systems' advice or perform the entire decision-making process on their own, often under time pressure and in critical situations.

Broadly, our goal is to investigate the effects that visualizing uncertainty has on decision-making tasks related to the identification and prioritization of targets made by air traffic operators. Before exploring these effects, we are interested in analyzing if uncertainty information is understood and taken into account during the analysis. Therefore, the research questions investigated are as follows:

1. Will air defense operators access, comprehend and take into account the uncertainty information associated with the input parameters values during the analysis carried out for identifying and prioritizing targets?
2. How does the visualization of uncertainty associated with the sensor data influence the analysis and decision tasks? In this study, we chose to explore the effects on three particular variables that lead to the following question: does the visualization of uncertainty affect operator's performance, confidence and workload?

In response to these research questions we hypothesized that (*H*1) the operators will access, comprehend and take into account the uncertainty information presented and (*H*2) the visualization of uncertainty provided will lead to greater confidence and workload, without lessen the performance. In order to test these hypotheses, we designed a controlled experiment where two groups of experts carried out identification and prioritization tasks, with and without visualization of the uncertainty associated with the sensor readings.

While the first two sections of this paper motivate the research carried out and introduce the necessary related work, Sections 3–6 present information regarding the analysis task carried out by the experts, the experimental setup, the visualization of uncertainty employed and the proof-of-concept prototype used during the experiments. The results are described and analyzed in Section 7, and discussed in Section 8. Finally, conclusions and future research directions are presented in Section 9.

2. Related work

2.1. Uncertainty visualization

Data is rarely absolutely certain. Harrower [8] argues that some things are unknowable or may not be knowable with precision and that this uncertainty arises from an imperfect understanding of the rare events and processes we want to study as well as from the imperfect, out-of-date and incomplete data that we must deal with. Griethe and Schumann [1], Skeels et al. [13] and Pang et al. [14] argue that error or uncertainty can be introduced in any step from the acquisition of the data, when filtering or processing the data or when presenting the data to an operator. Griethe and Schumann [1] further claim that uncertainty can be understood as a composition of different concepts such as error, imprecision, subjectivity and non-specificity. However, there seems to be no general agreement upon what is meant by uncertainty as well as how it should be visualized. MacEachren et al. [9] state that "[*i*]*nformation uncertainty is a complex concept with many interpretations across knowledge domains and application contexts* […]. [*W*]*e do not have a comprehensive understanding of the parameters that influence successful uncertainty visualization*, *nor is it easy to determine how close we are to achieving such an understanding*" (p. 139). Skeels et al. [13] further argue that by developing ways of visualizing the uncertainty associated with data, we can help users better understand and appropriately use this data. However, as further stated by the authors, uncertainty is not always expressed as a quantifiable probability and it might be difficult to express this uncertainty in textual and verbal descriptions. The difficulty of visualizing uncertainty is also highlighted by Zuk and Carpendale [6], who state that the task of including uncertainty information into a visualization, while at the same time maintaining ease of comprehension for both the data and the uncertainty is not easy.

The effects of uncertainty visualizations and the presentation of reliability information in civil security and military contexts have been investigated by [15–18]. Finger and Bisantz [15] present two studies in which degraded or blended icons were used to convey uncertainty regarding the identity of a radar contact as hostile or friendly. A classification study showed that participants could sort, order and rank icons from five sets intended to represent different levels of uncertainty. The second study compared the use of degraded icons and probabilities, non-degraded icons and probabilities and degraded icons only in a simulated radar exercise, where participants had to identify hostile or friendly contacts. The results showed that participants using displays with only degraded icons performed better. Thus, the authors indicate that people can understand and work with situational uncertainty conveyed through the use of degraded icons. This research was extended in Bisantz et al. [16], where several display methods were used in a missile defense game: icons represented the most likely object classification (with solid icons), the most likely object classification (with icons whose transparency represented the level of uncertainty), the probability that the icon was a missile (with transparency) and, in a fourth condition, participants could choose among the representations. Task performance was highest when participants could toggle the displays, with little effect of numeric annotations. As such, the authors once more support the use of graphical uncertainty representations, even when numerical presentations of probability are present. However, the participants of these studies were not experienced and one of the concluding remarks of the authors is that future work should extend these results to more operational settings and experienced users, a clear motivation for carrying out the experiments presented here. In the work of Neyedli et al. [18], the effects of using integrated/separated pie charts and mesh images depicting the reliability of a threat identification support system were evaluated. The participants in the study who used the mesh display were better able to discriminate hostile from friendly targets than the participants using the pie display. Further, the participants using the integrated display shifted their reliance level more optimally with changes in the reliability level. Nevertheless, no experts took part in their experiments (students or employees of the Department of