The Influence of Uncertainty Visualization on Decision Making: An Empirical Evaluation

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Abstract

Uncertainty visualization is a research area that integrates visualization with the study of uncertainty. Many techniques have been developed for representing uncertainty, and there have been many participant-based empirical studies evaluating the effectiveness of specific techniques. However, there is little empirical evidence to suggest that uncertainty visualization influences, or results in, different decisions. Through a human-subjects experiment, this research evaluates whether specific uncertainty visualization methods, including texture and value, influence decisions and a users confidence in their decisions. The results of this study indicate that uncertainty visualization may effect decisions, but the degree of influence is affected by how the uncertainty is expressed.

1 Introduction

Visualization has the power to increase the apparent quality of highly generalized or uncertain geographic data. Uncertainty visualization strives to bridge the gap between the imprecision of reality and the apparent precision of its digital representation to provide a more complete representation of data (Pang et al. 1997). Research has demonstrated that visualization of the uncertainty of complex spatial data can aid the process of decision making (MacEachren and Brewer 1995; Leitner and Buttenfield 2000; Cliburn et al. 2002). Although visualization environments do not necessarily constitute complete or all-inclusive views of every possible alternative, they can supply decision makers with a quick, and to a certain degree, reliable overview of reasonable solutions (Aerts et al. 2003).

The mere fact that a phenomenon is represented on a map may imply unwarranted authoritativeness in the data. Comprehensive analysis of a geographic dataset is facilitated by an integrated presentation of both the data and its uncertainty. Uncertainty in this context refers to uncertainty in input data, attribute data, model formulations, or graphical representation. Managing uncertainty for decision support involves quantifying the uncertainty present, and requires an understanding of how uncertainty propagates in the data, model, or simulation. Furthermore, it involves learning how to make decisions when uncertainty is present, and communicating that uncertainty to decision makers (Aerts et al. 2003). Researchers have responded to these challenges by developing concepts and techniques for the representation of uncertainty for use in decision support applications (Pang et al. 1997; Leitner and Buttenfield 2000; Cliburn et al. 2002).

This paper examines the results of a pilot study of decision-making based on maps with and without a representation of uncertainty, and reports results that suggest that uncertainty visualization has a significant influence on decisions. Specifically, our research focuses on the following:

- Does displaying uncertainty information result in different conclusions or decisions about the data?
- Does the inclusion of uncertainty result in a difference in expressed confidence about decisions or conclusions?

We examine relevant background literature, describe the methods and results of a human-subjects experiment we conducted, and discuss the experiment in the context of extending and generalizing its results. The results of this pilot study are preliminary findings, which will support an ongoing study of decision-making and uncertainty representation.

2 Background

2.1 Approaches to Uncertainty Visualization

Cartographic research offers a well-defined framework of guidelines for the display of different types of information. Recent research has theorized and demonstrated that some methods of depicting uncertainty may be superior to others; some suggested methods include supplementing thematic maps with added geometry or visual variables (on static or dynamic maps), or adding specific interactive capabilities on dynamic maps. Dynamic maps are a special type of map that includes maps that are interactive, animated or both. The pilot study discussed in this paper was designed to determine the degree to which the addition of uncertainty representation influences decision making, and, though interactive exploratory tools in a computer environment may prove important, we limited the scope of this study to the use of static maps. We look in particular, therefore, to previous studies of uncertainty visualization using paper maps.

MacEachren (1995) suggests three general methods for depicting uncertainty. The first two can be applied to static representations: first, representations can be compared with individual representations presented for an attribute and its associated uncertainty. Second, representations can be combined, where a single visualization presents both an attribute and its uncertainty – using appropriate visual variables, an attribute and its uncertainty are visualized by overlaying one on the other. The third method, possible in an interactive computer environment, is to utilize exploration tools that allow users to manipulate the display of both the data and their uncertainty (see also Howard and MacEachren 1996; Slocum et al. 2004). Fisher (1994) demonstrated that sound could be used in combination with animation for the representation of uncertain information.

Gershon (1998) proposed two general categories for techniques to represent uncertainty: intrinsic and extrinsic. *Intrinsic* representation techniques integrate uncertainty in the display by varying an object's appearance to show associated uncertainty. Such techniques include varying visual variables such as texture, brightness, hue, size, orientation, position, or shape (Gershon 1998). For example, finer texture or darker value could represent greater reliability and coarser texture and lighter values could represent unreliability (MacEachren 1992; Leitner and Buttenfield 2000; Slocum et al. 2004). MacEachren (1992) suggested that saturation is logical for depicting uncertainty, with pure hues representing reliable data and unsaturated hues representing unreliable data. Three years later, MacEachren (1995) proposed a new visual variable, "clarity," that would be particularly applicable to uncertain data representation. Cliburn et al. (2002) suggest that intrinsic methods provide a more general visualization of detailed uncertainty data, which non-technical users may prefer over extrinsic representations. *Extrinsic* techniques add geometric objects, including arrows, bars, and complex objects (such as pie charts), to represent uncertainty. This representation method implies that uncertainty is a variable separate from the data. Some of the more complex objects, such as error bars, may become confusing over large areas. Allowing the selection of specific regions or objects in an interactive exploratory environment may prevent complex objects from overwhelming the user (Cliburn et al. 2002).

2.2 Uncertainty Visualization for Decision Support

Decision support systems (DSS) have been defined as computer-based systems that integrate modeling and analytic tools with data sources, assist in the development, evaluation and ranking of potential alternative solutions, assist in the management and evaluation of uncertainty and enhance overall comprehension of problems and potential solutions (Mowrer 2000; Crossland et al. 1995). Although DSS incorporate inaccuracies (i.e. uncertainty), traditional (non-spatial) DSS do not provide a means for organizing and analyzing *spatial* data. Spatial decision support systems (SDSS) integrate the data and analytical models of traditional decision support systems with the spatial data organization and processing capabilities of GIS, remote sensing classification or spatial statistics, allowing decision makers to perform graphical analysis of spatial information (Cooke 1992; Sengupta and Bennett 2003; Mowrer 2000). As with the definition of a DSS, spatial decision support provide access to relevant information that otherwise might be inaccurate or unavailable. SDSS also provide detailed displays resulting in reduced decision time and enabling a better grasp of spatial problems due to better visualization of the problem to be solved (Crossland et al. 1995).

It has been argued that uncertainty information is a vital component in the use of spatial data for decision support (Hunter and Goodchild 1995; Aerts et al. 2003). Many techniques have been developed for communicating uncertainty in data and models for specific visualization applications, such as remote sensing, land allocation, water-balance models and volumetric data (Aspinall and Pearson 1995; Leitner and Buttenfield 2000; Bastin et al. 2002; Cliburn et al. 2002; Aerts et al. 2003; Lucieer and Kraak 2004; Newman and Lee 2004). Although cartography has a strong tradition of empirical research in map design and user comprehension, research into the effectiveness of uncertainty visualization as it relates to decision support is only beginning to emerge. Researchers have emphasized the need for empirical research to test the effectiveness of visual variables and their usefulness in depicting uncertainty (Evans 1997; MacEachren et al. 1998, Leitner and Buttenfield 2000; MacEachren et al. 2005).

In one study, MacEachren et al. (1998) developed and tested a pair of methods for depicting “reliability” of data on choropleth maps of cancer mortality information, and studied the effect of different visual depictions on accuracy of responses to tasks typical of epidemiological studies. They found that texture-overlay onto a choropleth map (a “visually separable” technique) was superior to a “visually integral” depiction (using color to represent both data and reliability) for decision-making using uncertainty. Additionally, Leitner and Buttenfield (2000) examined how the addition of attribute uncertainty information affects the decision-making process utilizing static maps, analyzing correctness and speed of responses to tasks relevant to urban planning. The addition of uncertainty with specific representation styles significantly increased the number of correct responses. They found that users identify the inclusion of uncertainty information as clarification and not as an addition of map detail.

3 Methods

At its most general, our study aimed to ascertain whether the inclusion of uncertainty information on a map (or set of maps) has a significant influence on decision-making. To do so, we conducted a human-subjects test consisting of a series of map reading and decision-making tasks that are representative of real-world tasks in water use policy and information dissemination. This test was administered using paper color maps of a variety of forms showing data sets from predictive models – and in some cases the uncertainty associated with those data sets – relevant to making decisions about water use. Specifically, we gave participants a series of different ranking tasks, identifying which regions were most vulnerable to water policy or water use changes, and which regions should be targeted in a marketing campaign for responsible water use. The survey instrument, including the maps, ranking tasks, and other questions, is described in detail below.

This study differs from similar studies in the past (MacEachren 1992; Leitner and Buttenfield 2000; Cliburn et al. 2002) in that we aimed to determine whether decision making *changes* as a result of incorporating uncertainty on maps, and not whether "correct" answers to specific questions were obtained or whether response times changed. To test for this, participants were randomly divided into two groups, one that was provided with uncertainty information present and one that was not. Participants in the first group (Group A) were asked questions related to maps of the data *and* their uncertainty, while those in the second group (Group B) were asked questions based on maps of the data alone. We assumed (with some caveats, discussed below) that, if we found any significant differences between average rankings from Group A and those from Group B, they could be attributed to the presence of uncertainty information on the maps.

Efforts were made to make the two groups otherwise similar. The questions for each group were identical, with the exception that surveys in Group A included questions and introductory statements referring to the uncertainty of the data. Base maps and color schemes were kept the same for both survey sets. In addition, the data on the maps were identical for each question, except, as mentioned above, the maps for the Group A surveys included representations of uncertainty. These measures were designed to help ensure that any variations between the groups were due to the inclusion of uncertainty.

In this study, we also sought to examine subtle differences in the connotations of the terms "certain" and "uncertain." In the survey and on the maps in Group A, some questions referred to the "certainty" of the data, while others refer to the "uncertainty" of the data. The concepts are, of course, similar in that they can both be either qualitative ("this value is uncertain") or quantitative ("this value is 80% certain," which is equivalent in this study to "this value is 20% uncertain"). Throughout the remainder of this document, we use the term "uncertainty visualization" to refer to both concepts.

The complete survey took approximately 15 to 20 minutes to complete. A majority of participants were students at Arizona State University, with some participants being from local planning and engineering companies.

3.1 Survey Overview

The first page of the survey identified the goal of the survey and provided a brief description of the participants' role in the survey. These introductory statements were purposely vague in order to avoid biasing Group B (our control group), stating that the goal of the project was simply to analyze the effects of specific visualization techniques on decision-making (without making any mention of uncertainty). Several pages, discussed in turn below, followed, each with its own distinct map or maps and set of questions. The maps (an example of which is shown in Fig. 1) depicted predicted water consumption based on changes in households, population and/or income in a hypothetical region. Each set of questions was meant to simulate tasks typical of decision-making. A brief discussion of the purpose of each map follows.

3.1.1 Map 1

Map 1 was a simple choropleth map, as in Figure 1, showing water consumption in the hypothetical region. This map and its associated questions were intended to identify participants' basic ability to read and interpret maps. Responses to these questions from Groups A and B would be compared to ensure that the groups represented similar map-reading abilities. Participants were asked to identify areas (among four circled and labeled sub-regions) of greatest growth and to make decisions about where to start a water conservation awareness campaign. Because this section was meant to evaluate basic map reading abilities, neither survey represented or asked about uncertainty for these questions.

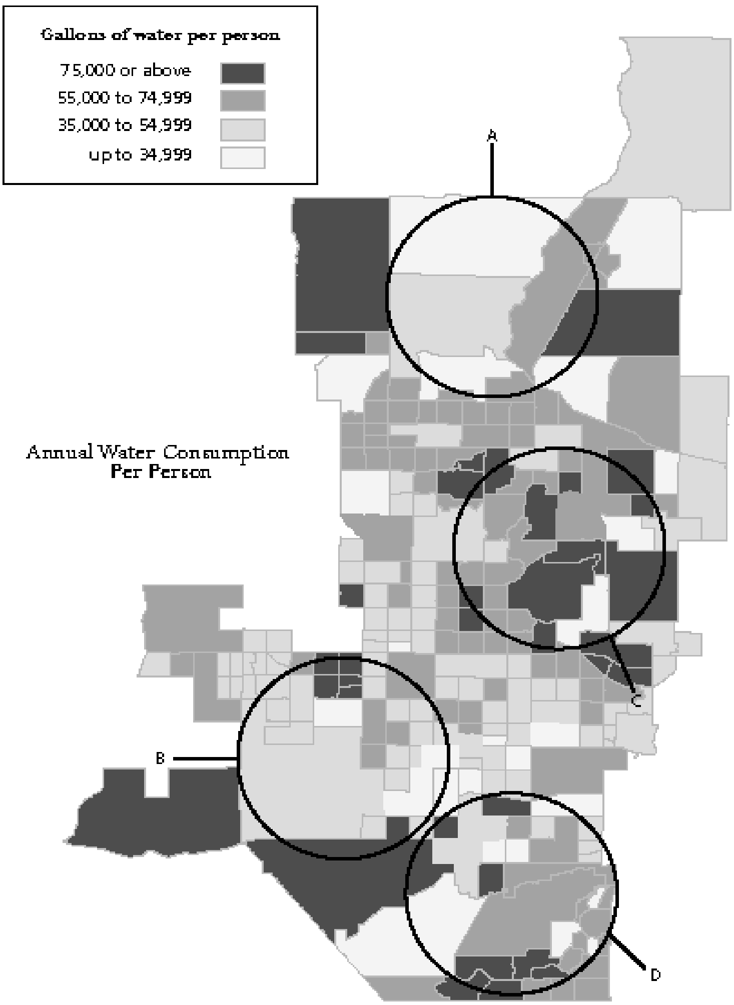

Fig. 1. Map 1 with task "identify region (A, B, C, or D) with the highest rate of water consumption per person"

3.1.2 Map 2

The questions for map 2 were intended to compare decisions made with (in Group A) and without (in Group B) representation of the relative *certainty* of the data. In both groups, we presented data with identical choropleth maps (but different from those in map 1). In Group A, we depicted the certainty of the data in a second choropleth map with lightness differences representing the certainty. Group B was not provided a second map in this section of the survey. We presented a “story problem” to participants, where they were in charge of determining where a media campaign to educate the public about water conservation should begin. The story problem explained that the goal for the task was to release the media campaign first in the region with the highest predicted increase, and then if the campaign was successful, to release it in the area with the next highest predicted increase and so forth. Based on this task, participants ranked the regions from highest to lowest predicted increase. They were also asked to identify their level of confidence in their decisions.

3.1.3 Map 3

The questions for map 3 were also intended to compare decisions made with and without uncertainty information. Once again, participants saw choropleth maps of predicted water consumption. Groups A and B saw identical thematic data in map 3, with identical color schemes and class breaks (map 3, however, depicted a different theme, in the same hypothetical region, than that in maps 1 and 2). Participants in Group A this time saw a bivariate choropleth map, with a depiction of uncertainty using a texture overlay, with uncertain data overlaid with hatch marks and more certain data with no texture overlay (MacEachren, Brewer, and Pickle (1998) depicted uncertainty in a similar manner in their study). Group B was shown only the univariate choropleth map. Once again, we presented a “story problem” to participants, where they were in charge of prioritizing four circled sub-regions to receive infrastructure improvements. Participants ranked the priority for each sub-region and identified their level of confidence in their decisions. Otherwise, the maps for the two groups were the same.

3.1.4 Map 4

Map 4 was only presented to participants in Group A. Map 4 was identical to map 1, except that certainty information was included as a texture overlay, with three levels of certainty represented with different texture densities. We asked the same question for map 4 as that for map 1. This allowed for within-subject comparison within Group A based on maps with and without certainty; with map 4, we would be able to determine if the certainty information resulted in different decisions made by the same person, and if the participants actually used the certainty information presented.

3.1.5 Exit Questions

Finally, we asked open-ended questions meant to determine if the maps were interpreted as effective decision-making tools (to both groups), whether uncertainty/certainty information was seen as negative or positive (to group A only), and whether the uncertainty information was viewed as useful for decision making (to group A only).

4 Pilot Study Analysis and Results

We collected the following data: rankings of sub-regions of the maps according to water-use decision making for each map and participants' confidence levels and opinions for each map. Responses to corresponding questions were compared between Groups A and B (and within Group A in the maps 1 and 4 comparison) to determine the significance of the variation between responses.

4.1 Analysis

Three types of information obtained during the study were examined to address the question of whether the representation of uncertainty affects decisions. We examined the differences in both rankings and confidence in those rankings between Groups A and B. Responses to open ended questions about the inclusion of certainty/uncertainty information were examined for Group A.

4.1.1 Ranking Comparison

Participant rankings for the questions for maps 1 through 3 were compared between the two Groups. For each map, participants ranked four regions (region A-D) on a scale of one to four, with one being the highest (priority, increase, consumption) and four being the lowest (priority, increase, consumption). To facilitate the analysis, we assigned each region a numerical value based on the ranking they received (for example, if the ranking was

ABCD, region A would have value 1, B would have a value of 2, etc.). Based on these values, we calculated the average ranking for each region for the Groups (region A had an average value for each Group A and Group B, as did regions B, C, and D). We then calculated the difference between the average values for each region (Group A minus Group B), and found the mean (absolute value) of all of these differences, for each map (1, 2, and 3). Our null hypothesis in each case was that there would be no difference between the rankings between Groups A and B. We evaluated this hypothesis by calculating a 95% confidence interval around the mean difference: if the participants in Groups A and B ranked the regions the same way, this confidence interval should include zero.

From Group A, we also compared the rankings for map 1 and those for map 4. The absolute value of the difference between the rankings for each region was calculated for each participant. A change in ranking from #4 to #1 would result in a score of three (four minus one), and a change from #2 to #4 would result in a score of two (four minus two). The minimum score between sets of rankings is, of course, zero, and the maximum is eight (a complete reversal: 4-3-2-1 to 1-2-3-4). Again, our null hypothesis was that there would be no difference between the rankings from map 1 (without uncertainty mapped) and map 4 (with uncertainty). We evaluated this hypothesis by calculating a 95% confidence interval around the mean difference for all participants: if the rankings from map 1 and map 4 were similar, this confidence interval should include zero.

4.1.2 Confidence in Rankings

For each ranking question, we also asked about the participant's confidence in the ranking decision. Participants identified their level of confidence on a five-point Likert scale from "not confident" (1) to "completely confident" (5). For each of the maps, we calculated the mean value for each Group and performed a two-sample t-test; our null hypothesis in this case was that there would be no difference between the mean confidence levels for each map between the two Groups.

4.1.3 Opinion Questions

The last four survey questions asked the uncertainty group participants to give their opinions about whether the inclusion of uncertainty information made them more/less confident in their decision, how the inclusion of uncertainty affected their decision and whether they viewed the inclusion of uncertainty/certainty information as negative. The analysis for these results consists of a summary of responses.

4.2 Results

We conducted the pilot study with volunteer participants sampled from among undergraduate and graduate students in the departments of Geography and Planning, as well as from professionals and decision makers in private planning and engineering firms. We collected 92 surveys in total, 48 in Group A and 44 in Group B (uneven because of incomplete responses and the randomized distribution between Groups). Of those 92, 87 were students and five were professionals[1].

4.2.1 Map 1

All participants were able to identify the area of greatest water consumption in map 1. In this instance, the correct answer is important in assessing whether participants understand the information presented in the map, and if we could reasonably compare Groups A and B. More than 83 percent of participants correctly ranked the regions from highest to lowest consumption.

When asked to identify the area where a water conservation awareness campaign should begin, over 90 percent recognized the region depicting the highest water consumption.

Table 1 identifies the results of the t-test for the average level of confidence in the rankings made for each subgroup. The results support the null hypothesis that there was no difference in rankings between the two groups. Based on these results we concluded that participants were drawn from the same population and that participants were able to recognize relevant spatial patterns represented in a choropleth map.

Table 1. Map 1 reading comparison

	Group A		Group B
Mean	3.73		3.86
Variance	0.75		0.86
N	48		44
hypothesized mean difference		0.00	
Df		88	
$t_{observed}$		0.72	
t_{crit}		1.66	
$p(t_{observed}<t_{crit})$		0.24	

[1] We sent 15 surveys to professionals; only 5 were returned completed. The rate of return for students (87 of 95) was higher, presumably because we remained in the classroom with the students – unlike the professionals – while they completed the survey.

4.2.2 Map 2

Figure 2 summarizes the rankings for map 2, and Table 2 summarizes the mean ranks for each sub-region, by Group, and the confidence interval for the overall mean difference. Our test showed evidence of a significant difference in rankings between those from Groups A and B (the 95% confidence interval does not include zero, and our null hypothesis is rejected).

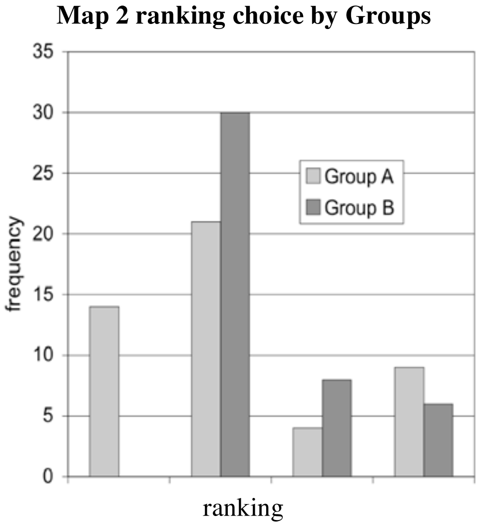

Fig. 2. Three common ranking orders for map 2: one popular ranking order for Group A was never chosen by Group B participants

Table 2. Map 2 ranking comparison

	Group A	Group B	Absolute difference
Mean rankings			
Sub-region A	3.04	3.77	0.73
Sub-region B	1.21	1.45	0.24
Sub-region C	2.29	1.84	0.45
Sub-region D	3.25	2.93	0.32
mean difference			0.44
σ			0.21
95% confidence interval (±0.30)		(0.14, 0.73)	

Table 3 identifies the results of the t-test for the average level of confidence in the rankings made for each subgroup. The average level of confidence expressed in both Groups was somewhat to almost completely confident (values of 3.46 and 3.61 out of 5.00). We cannot conclude that, in the case of map 2 and its associated ranking task, there was a statistically significant difference between the confidence ratings depending on the presence of certainty information

Table 3. Map 2 confidence comparison

	Group A		Group B
Mean	3.46		3.61
Variance	1.02		1.17
N	48		44
hypothesized mean difference		0.00	
Df		88	
$t_{observed}$		0.71	
t_{crit}		1.66	
$p(t_{observed}<t_{crit})$		0.24	

4.2.3 Map 3

Figure 3 summarizes the rankings for map 3, while Table 4 summarizes the mean ranking for each sub-region, by Group, and the confidence interval for the overall mean difference. Our test showed evidence of a significant difference in rankings between those from Groups A and B (the 95% confidence interval does not include zero, and our null hypothesis is rejected).

Table 4. Map 3 ranking comparison

	Group A	Group B	Absolute difference
Mean rankings			
Sub-region A	3.33	3.02	0.31
Sub-region B	2.19	2.98	0.79
Sub-region C	1.69	1.39	0.30
Sub-region D	2.58	2.39	0.20
Mean difference			0.40
σ			0.27
95% confidence interval (±0.27)		(0.03, 0.77)	

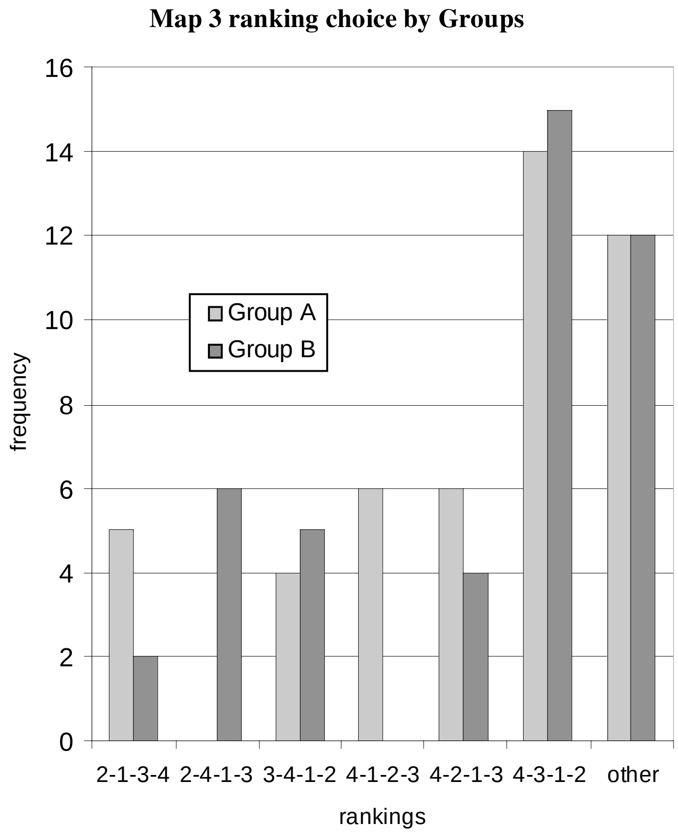

Fig. 3. Differences in rankings of sub-regions with and without uncertainty: the 2-4-1-3 ranking was popular among those who were not provided uncertainty (Group B), while none that were provided uncertainty (Group A) chose that ranking

Table 5 identifies the results of the t-test for the average level of confidence in the rankings made for each subgroup. The average level of confidence was somewhat confident (values near three). As can be seen from the results, it cannot be concluded that there is a statistically significant difference between the confidence in rankings for map 3 between those from Group A and Group B.

Table 5. Map 3 confidence comparison

	Group A		Group B
Mean	2.98		2.86
Variance	0.99		1.03
N	48		44
hypothesized mean difference		0.00	
Df		88	
$t_{observed}$		0.56	
t_{crit}		1.66	
$P(t_{observed}<t_{crit})$		0.29	

4.2.4 Map 1 vs. Map 4

Figure 4 summarizes the absolute difference in rankings for maps 1 versus 4 for each Group A participant. Over half (25 of 48) participants altered their ranking from map 1 to map 4 (shown on the graph as non-zero absolute ranking-difference scores), supporting the hypothesis that the presence of uncertainty on the maps influences decision-making. As discussed in section 4.1.1, a high raking-difference score indicates a significant change in ranking.

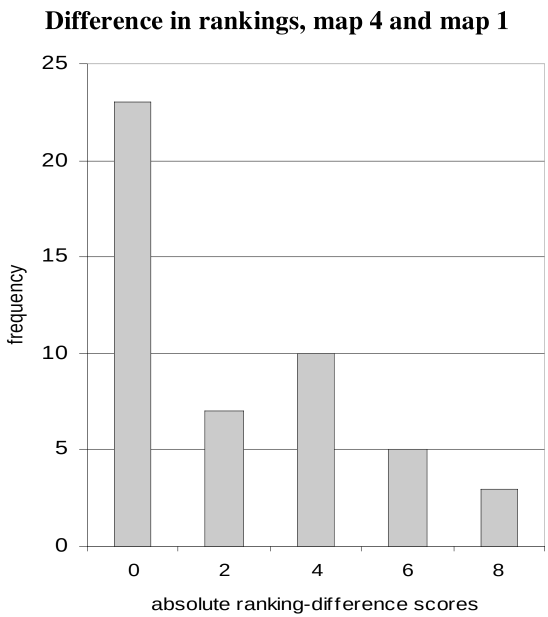

Fig. 4. Ranking-difference score frequency, comparing rankings with and without uncertainty information depicted. Non-zero scores indicate a change in ranking (the scoring is discussed in section 4.1.1)

Table 6. Map 1 v. Map 4 ranking-difference scoring

	ranking-difference scoring
Mean	2.27
σ	2.62
95% confidence interval (± 0.76)	(1.51, 3.03)

Table 6 summarizes the difference between and the confidence interval for the paired rankings. Our test showed evidence of a significant difference in rankings between Maps 1 and 4 (the 95% confidence interval does not include zero, and our null hypothesis is rejected). We can thus say that rankings changed when certainty was depicted. However, the average difference of 2.27 indicates that the change in rankings were subtle and not completely reversed (i.e. they may have reversed the middle values but kept the highest and lowest rankings the same).

Figure 5 summarizes the difference in confidence expressed for the rankings provided for map 1 and map 4. A negative value indicates that the participant had a higher degree of confidence for the decision made with the map without certainty information and a positive value indicates that they had a higher degree of confidence in the ranking made with the certainty map.

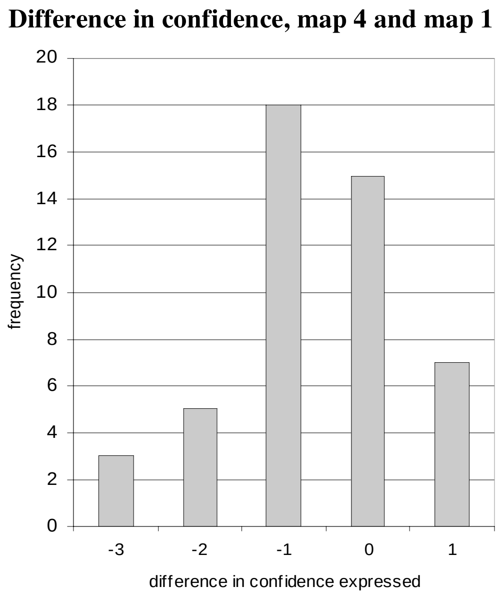

Fig. 5. The difference in confidence expressed between map 4 and map 1. A negative value indicates that confidence expressed for map 4 (with uncertainty presented) was lower than then expressed for map 1 (without uncertainty)

Table 7. Map 1 v. Map 4 difference in confidence self-scoring

	confidence scoring difference
Mean	-0.62
σ	1.13
95% confidence interval (± 0.31)	(-0.97, -0.32)

Table 7 summarizes the difference in expressed confidence for the paired results as well as the confidence interval for the mean difference. The null hypothesis that there is no difference between confidence scores with and without uncertainty depiction is rejected. The average difference in the level of confidence for the two questions was negative, indicating that confidence significantly decreased with the inclusion of certainty information.

4.2.5 Opinion Questions

Based on the opinion questions, most participants in Group A indicated that the inclusion of uncertainty information would influence their decisions, but that they would feel more confident if they had other data sources in addition to the uncertainty/certainty maps. Of Group A participants, 46 percent viewed uncertainty information as negative and certainty information as positive, 31 percent viewed neither uncertainty or certainty information as negative, 10 percent viewed both uncertainty and certainty as negative and the remaining 13 percent did not respond to the exit questions. When participants viewed the uncertainty or certainty information as positive, they also viewed the inclusion of the information as positive.

5 Summary of Results

The results for each maps ranking task showed a statistically significant difference in the rankings between Group A and Group B for maps 2 and 3, as well as within Group A for map 1 and map 4. The 95 percent confidence interval for each map comparison did not include zero, and we rejected the null hypothesis that there was no difference between responses based on maps with uncertainty and maps without uncertainty. The results for the confidence expressed identified no statistically significant difference between the confidence expressed for Group A and Group B responses for map 2 and map 3, however, there was participants expressed decreased confidence in their results for map 4 compared to their responses for map 1. These results and potential implications for future research are discussed in detail in the following section.

6 Discussion

The results of this study suggest that uncertainty visualization may influence decisions. The analysis suggested that there was a difference in rankings when both uncertainty and certainty information were included, although the differences were not extreme. Results for the expressed confidence in the decisions made found no statistical difference between confidence levels for map 2 and map 3; however, participants expressed decreased confidence when responses to map 1 and map 4 from Group A were compared.

This discrepancy in confidence level results suggests that factors other than inclusion or non-inclusion of uncertainty representations may be influencing confidence. For example, the ranking task in map 2 may have been more difficult than in map 4, or the addition of uncertainty in map 3 more obviously relevant in the ranking task than in map 2. Other factors that may have influenced expressed confidence include the complexity of the data or uncertainty classifications—map 3's general binary classification of data as certain or uncertain was less complex than map 4's representation of three degrees of certainty. The provision of more detailed information in map 4 may have contributed to the difference in confidence.

There are a number of factors about the administration of this survey that could be modified if it is to be repeated. The response rate among decision makers was below 50 percent. Increasing this response rate would allow comparisons between decision makers and others. Administering a paper-based survey to professionals in a variety of locations can be logistically prohibitive. The transition to a web based survey may lower the threshold for participation and increase the response rate with this group (Aerts et al. 2003). In addition, the survey instructions should more clearly identify that the region and data were hypothetical in nature and that the maps are not related (i.e. information in the first map should not influence responses to questions about map 2). In the exit questions, several participants noted that they attempted to utilize their knowledge of the region to interpret the data; however, since the regions geometry and size had been altered for the study maps and the data was created specifically for the study, this background knowledge made the maps confusing. Providing clearer instructions at the beginning of the survey would help to avoid this issue.

Extensions of the study could also include a third and fourth subgroup of participants. The maps should be divided into data only, data and uncertainty visualization, data and certainty visualization and data, and tabular or written description of data uncertainty. The methods of visualization should include varying levels of information detail, ranging from a simple classification of certain/uncertain to a range of saturation/value levels to represent a range of uncertainty/certainty values, as well as supporting information such as geographic reference data and detailed statistical information. These additions would identify whether uncertainty and certainty affect users differently and whether the inclusion of supporting information increases confidence.

7 Conclusions

The incorporation of uncertainty information into GIS applications and data sets is a vital component for the critical examination of spatial data for decision support. In this paper, we focused on the effect of a spatial representation of uncertainty on decision-making. We developed a pilot human-subjects experiment to evaluate the influence of uncertainty visualization in decision-making. Analysis of these tests suggests that the incorporation of a display of the spatial distribution of uncertainty information can significantly alter the decisions made by a map user. Our research, at this stage, is limited to tasks specific to water use and policy decision support, and is also limited to the use of static maps with specific uncertainty representation methods. There are many techniques that have been developed for communicating uncertainty in data and models for specific visualization applications, and research into the effect of these techniques on comprehension is ongoing. As shown in this study, uncertainty visualization may effect decisions, but the degree of influence is affected by how the uncertainty is expressed. We will use the results of this preliminary study to support future research into the effects of other uncertainty representations on user comprehension and decision-making.

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