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Visualising Uncertainty for Decision Support

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Joint and Operations Analysis Division
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ABSTRACT

Uncertainty is inherent in all real world settings and it creates ambiguities that make decision making complex and difficult. For decades, uncertainty visualisation has been a prominent topic in the research of military decision making. Even if data is free from uncertainty, errors can occur in the process of turning the data into the 'picture'. Ignoring the fact of information uncertainty could lead to severe consequences in the military domain. This report presents an overview of the theoretical concepts and definitions of uncertainty, and the uncertainty visualisation techniques that have been investigated to date. It discusses the literature on the impact of uncertainty visualisation on decision making, and introduces recommended guidelines and systematic strategies for uncertainty visualisation. Finally, it discusses how this work can be applied to support situation awareness and decision making in the Australian Defence Force's Joint Operations Command.

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Visualising Uncertainty for Decision Support

Executive Summary

Military commanders are typically required to make critical decisions and develop plans, using large and complex collections of data, in a limited time frame. They must do this without precise knowledge about the operating environment or the intent, capabilities or location of the adversary. It is important that commanders understand the associated uncertainties so that they can understand and mitigate the operational risks involved in this inherently risky enterprise. Therefore it is important for decision support tools to make users aware of the uncertainties in the information being displayed in an appropriate and timely manner, while avoiding information overload. However, most visualisation techniques have been designed around the assumption that the data being visualised is free from uncertainty. This report reviews the concepts, techniques, and effectiveness of visualisation approaches for uncertainty presented in the literature, and looks at how these could be applied to enhance situation awareness in the Joint Operations Command (JOC).

Uncertainty can come in many forms, with 11 different types of uncertainty discussed in the literature:

- Accuracy – the difference between observation and reality
- Precision – the quality of the estimate or measurement
- Completeness – the extent to which information is comprehensive
- Consistency – the extent to which information elements agree
- Lineage – the pathway through which information has been passed
- Currency – the time span from occurrence to information presentation
- Credibility – the reliability of the information source
- Subjectivity – the extent to which the observer influences the observation
- Interrelatedness – the dependence on other information
- Experimental – the width of a random distribution of observations
- Geometric – the region within which a spatial observation lies.

Each of these different types of uncertainty applies to different types of information, and can be quantified, and thus represented, in different ways. These uncertainties can be introduced at any stage during an information processing pipeline:

- Acquisition – introduced by the measurement or sampling processes
- Transformation – introduced by processing algorithms or fusion processes
- Visualisation – introduced by visualisation artefacts or filters.

Indeed, the act of trying to account for, quantify, and visualise uncertainties could potentially introduce more uncertainties into a system, and so it is important to understand the nature of any uncertainties and their impact on the quality of decision making. It is particularly important to ensure that attempting to represent uncertainty does not introduce artefacts that obscure, clutter, or interfere with the information to be displayed. Visualisation approaches that have been used for representing uncertainty fall into two general categories:

- intrinsic representation techniques that integrate uncertainty by varying the appearance of the data (e.g. shape, texture, brightness, opacity and hue)
- extrinsic representation techniques that add geometry to describe the uncertainty (e.g. arrows, error bars and charts).

The choice of visualisation approach depends on the nature of the uncertainty and the application context. For geospatial contexts, five intuitive categories of uncertainty representation have been suggested:

- modification of graphical attributes, such as colour, texture, blurring, and opacity
- addition of artefacts, such as glyphs, contours, and iso-surfaces
- animation of graphical attributes to illustrate the expected variability
- non-visual techniques, such as acoustic and haptic feedback coupled with a visual display
- user interaction, such as information pop-ups on mouse hover over a data feature.

Much of the work covered in the literature has focussed on the technical feasibility and implementation of these approaches, with little analysis of their perceptual or cognitive value, and little systematic evaluation done on the general effectiveness of these approaches. Thus, studies need to be tailored to particular user contexts. There have been empirical studies carried out on the effect of uncertainty on decision making, which found marked differences in performance between experienced and inexperienced users. The decision times for experienced users were not affected by uncertainty, while those of inexperienced users were significantly increased. Interestingly, visualisation of uncertainty has been found to improve decision making performance for relatively easy tasks, but not when dealing with more difficult tasks when, perhaps, other considerations dominate. How user experience maps to subjective task difficulty could be an interesting consideration that makes the selection of participants for empirical studies particularly important when studying the effectiveness of uncertainty representation techniques. Clearly, participants in empirical studies need to be representative of the skills and experience of the target user group.

Several empirical studies have also looked at the effects of different uncertainty visualisation approaches on decision making in different contexts. Dynamic uncertainty representation techniques (e.g. animation) were generally found to be less effective than static techniques (e.g. glyphs) in decision making tasks. Somewhat surprisingly, the addition of textual annotations of confidence to a glyph representing the degree of uncertainty was found to give poorer performance than the glyph alone in a target identification task, perhaps indicating information overload. In other studies, different uncertainty representations were also found to suit different user requirements in the same application, suggesting that some degree of tailoring may be required to meet multiple user roles. This should be treated with caution however, as studies have also shown that user satisfaction with information products does not necessarily coincide with improved situational awareness in general, and user preferences for uncertainty representation techniques do not necessarily coincide with improved decision making performance in particular. System metrics and governance frameworks may be needed to help manage this complexity.

Other approaches to uncertainty visualisation could use the method of representation itself to attribute confidence in the information presented. For example, users have greater confidence in information presented textually than the same information presented by a virtual human avatar. Thus, in this approach information with low uncertainty could be presented to the user as text, while information with high uncertainty could be presented to the user by an avatar. Further studies could also explore how users attribute confidence to information presented using other visualisation modalities.

There are limited guidelines available for the development of applications utilising the various approaches considered when representing multiple types of uncertainty in a decision making context. More study is needed in how to depict multiple forms of uncertainty in the same display, and how adding multiple types of uncertainties to visual displays affects the users' understanding. General guidelines for visualisation can be applied to help formulate an uncertainty visualisation approach suitable for a particular context, once the relevant components of uncertainty, their relationships to the data, and the desired decision making outcomes are understood. User centred design, iterative approaches to development, and methods for assessing relevant performance metrics, are considered crucial given the sensitivity of decision making outcomes to context, user experience, and user roles.

The situational awareness requirements of the Australian Defence Force's Joint Operations Command (JOC) range across the spectrum of ADF operations to achieve national strategic objectives. The users in JOC need to access, integrate and visualise a diversity of information across the Defence Enterprise including military text messages, unstructured documents, military databases and open-source content from civilian producers. Furthermore, this needs to be tailored to support a variety of dynamic operational needs, because the users are unlikely to be subject matter experts in each of the data sets being integrated. It is crucial that they understand the uncertainties associated with the information being displayed so that they can mitigate operational risks.

In this context, the sources of uncertainty include:

- Incompleteness due to parsing errors from poorly formatted structured content
- Geometric uncertainties associated with geospatial content

- Ambiguities and incorrect entity associations from unstructured content
- Incomplete metadata
- Inconsistent or incompatible schema and/or standards associated with structured content
- Inconsistent information from multiple sources
- Interrelatedness of content and/or corrections
- Currency of content
- Lineage and/or credibility of content
- Incompleteness where data aggregation would raise the classification above the system's accreditation
- Incompleteness due to the pagination of search results, map scale and/or viewpoint settings in geospatial displays
- Incompleteness due to object clustering used to reduce visual clutter
- Interference between overlapping visualisation layers and/or overlapping symbology.

Some of the approaches discussed in the literature that could be used to visualise these uncertainties include:

- Combining representation techniques such as opacity, blurring, and degraded icons to visualise compounded uncertainty (e.g. geospatial uncertainty, information currency, and status ambiguity in incident reports or emergency events)
- Highlighting inconsistencies in the information presented through colour coding
- Highlighting the credibility/lineage of content through colour coding
- Providing a visual indicator of missing/incomplete information, with elaboration provided through user interaction (e.g. mouse hover/click)
- Providing multimodal content through audible or haptic feedback while interacting with the visual display
- Using different visualisation modalities to confer different levels of confidence in the information presented (e.g. use of an avatar to confer lower levels of confidence in uncertain information).
- Allowing users to choose appropriate uncertainty visualisation techniques that suit their current task and experience, based on user and role models.

Empirical studies and further conceptual refinement are needed to target the particular requirements of JOC users. Significant barriers to these studies will be the availability of experienced users for empirical evaluation, and the dynamic nature of their visualisation requirements across a broad range of information types and associated uncertainties. The dynamic nature of these requirements means that many of these users may be unfamiliar with a particular task or display, which may make it easier to find participants representative of this target group. It also indicates that visualisation of the associated uncertainties has the potential to provide significant benefits to decision making performance in this context.

Finally, how decision making with uncertainty translates to operational risk is an area that requires further study. In the studies presented in the literature the performance of the decision maker was evaluated using metrics such as response time and the user's confidence in the outcome. Whether the representation of uncertainty translates to a better appreciation of operational risk, and more effective mitigation strategies, has not been considered in this work. Studies that model and evaluate operational risk, and/or include operational red-teaming, could help address this question.

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More recently he has worked on Situational Awareness technologies supporting HQJOC, including R&D towards a Higher Level Common Operating Picture (HiCOP) incorporating aspects of a User Defined Operating Picture (UDOP) and multimedia narrative

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1. Introduction

1.1 Motivation

Visualisation is the communication of data in a visible form that brings out relationships and features in data. The main goal of data visualisation is to communicate information clearly and effectively through graphical means (Friedman, 2008). Effective visualisation makes massive and complex data understandable and usable in an intuitive way to help users analyse and reason about it.

Most scientific data sets are not considered complete without an indication of some measure of uncertainty such as error, accuracy or level of confidence. However, traditional visualisation approaches have usually been developed based on the assumption that all data are exact and, thus, the visual representation of uncertainty has been overlooked (Lapinski, 2009). Uncertainty could be depicted in a variety of formats ranging from simple text to dynamic graphical representations. Increasingly, understanding how to effectively display uncertainty information is becoming an important topic across many domains such as cartography, geographic visualisation and scientific visualisation.

According to Finger and Bisantz (2002) the question of how to represent uncertainty is important from two perspectives. Firstly, there is the theoretical need to determine the manner in which different representations or display formats may impact users' understanding of the uncertainty. This subsequently affects the decisions and actions made based on these different representations. Secondly, it is necessary to determine how best to display this information to users, particularly when there is uncertainty associated with a large number of objects or data points.

Indications of uncertainty in visualisation are crucial to understanding the "reliability" of information, and consequently affect decision making (Deitrick, 2007). Olston and Mackinlay (2002) argued that information visualisation tools should make users aware of the presence, nature, and degree of uncertainty in the data, otherwise users may draw inaccurate conclusions, potentially leading to costly mistakes. Indeed, command and control (C2) issues in regards to uncertainty visualisation have long been regarded as a difficult topic since the commander has to make decisions in a limited time frame with information that comes from varied sources, in many formats, with a continuum of validity (Summers et al., 2005).

As decision makers become more reliant on data visualisation capabilities to support their decision making, the importance of visualising uncertainty in the data grows. However, the actual task of visualising this uncertainty becomes problematic as it is not easy to include additional uncertainty information into an existing visualisation without introducing visual clutter and impairing comprehensibility (Riveiro, 2007). Uncertainty visualisation increases the dimensionality of the data (e.g. multivariate and statistical visualisation techniques (Pang, 2001)), and the richness needed in the display to avoid obscuration of information.

In this report we review some of the approaches suggested for visualising uncertainty, and explore how they may be applied to decision support tools. We begin by summarising the different types and sources of uncertainty identified in the literature. We then examine different methodologies that have been suggested for the visualising various types of uncertainty relevant to situation awareness. Next we examine specific empirical studies on the effect of uncertainty on decision making, and the effectiveness of some of the approaches used for uncertainty visualisation in this context. We then suggest some guidelines and strategies for uncertainty visualisation design, and how these techniques can be utilised for situation awareness in the Australian Defence Force's Joint Operations Command.

2. Information Uncertainty

2.1 Types of uncertainty

Good practice requires statements of accuracy by which the reliability of results can be understood and communicated. In MacEachren et al. (2005), when inaccuracy is known objectively it can be expressed as "error" otherwise the term "uncertainty" applies. Hunter and Goodchild (1993) define uncertainty as the degree to which the lack of knowledge about the amount of error is responsible for hesitancy in accepting results and observations.

In Pang et al. (1997), the authors considered three types of uncertainty in their discussion:

- statistical - either given by the estimated mean and standard deviation which can be used to calculate a confidence interval or an actual distribution of the data
- error - a difference between a known correct datum and an estimate
- range - an interval in which the data exist, but which cannot be quantified into either the statistical or error definitions.

In general, uncertainty is understood as a composition of different concepts. It has many interpretations across various domain and application contexts (Griethe, 2005). Thomson et al. (2005) have constructed a typology for uncertainty based on Gershon's taxonomy (Gershon, 1998) and Pang et al.'s classification (Pang et al., 1997) (see Table 1).

Table 1 Term and general definitions for uncertainty categories (modified from (Thomson et al., 2005))

Category	Definition	Attribute Examples	Location Examples	Time Examples
Accuracy/error	Difference between observation and reality, usually estimated based on knowledge of the measurement / estimation device and of phenomena in the work.	counts, magnitudes	coords., buildings	+/- 1 day
Precision	Exactness of measurement /estimate, derived from parameters of the measurement, estimation device, and/or procedure.	nearest 1000	1 degree	once per day
Completeness	Extent to which information is comprehensive.	75% reporting	20% cloud cover[1]	5 samples in 100
Consistency	Extent to which information components agree. This is a more general definition than that found in formal standards for spatial data	multiple classifiers	'from a place' vs 'for a place'	5 say M; 2 say T

[1] Does the 20% measure in this case tell you that there is a 20% chance of 100% cloud cover at any location, or that at any location there is a 100% chance of 20% cloud cover?

Lineage[2]	Conduit through which information has passed. This is a complex category that has at least the following subcomponents: number of individuals, organizations, processes through which information moves; specification of which individuals, organizations, or processes	transformati ons	# of input sources	# of steps
Currency	Currency depends on the time span from occurrence through information collection /processing to use, and the context. E.g., year-old data about vehicles parked in a factory loading bay is less certain to be current than year-old data about location of the factory	census data	date of map production	5 hours ago
Credibility	Combination of factors such as reliability of information source. Certainty may be based on past experience, e.g., the analyst is correct 85 percent of the time, or on categorization of the source, e.g., U.S. analyst versus a non-U.S. informant; motivation, experience, or other factors.	U.S. analyst; informant	knowledge of place	reliability of model
Subjectivity	The extent to which human interpretation or judgment is involved in information construction. This component of uncertainty is, of course, difficult to assess—and that assessment will have some level of subjectivity.	fact / guess	local / outsider	experienced/ inexperienced
Interrelatedness	Source independence from other information. This is a common standard used in the news media to assess certainty that a story is authentic	same author	source proximity	time proximity

Potter (2010) suggested two additional types of uncertainty, depending on how they arise in the data set:

- **Experimental uncertainty**
  In mathematics, uncertainty is closely related to probability theory which describes the occurrence of some events as random. Foody and Atkinson (2002) simply described uncertainty as a 'quantitative statement about the probability of error'. Taylor and Kuyatt (1993) proposed guidelines for expressing the uncertainty of measurement results and defined experimental uncertainty as the standard deviation of a collection of measured results. This type of uncertainty is derived

[2] This is also known as 'provenance'.

from running an experiment numerous times, or performing a non-deterministic simulation in which the outcome varies after each run (Potter et al., 2012).

- **Geometric uncertainty**
  Geometric uncertainty arises when the spatial position of some or all of the data set is in question. This type of uncertainty may describe the amount of possible variation between a data point and the true location, or may describe a boundary region within which the data point will be positioned. For example, Figure 1 illustrates that the yellow spheres represent the spatial uncertainty of the points on the surface. This technique could be useful to understand and analyse data more intuitively because the user can understand not only where the location of the surface is, but also the relative quantity of uncertainty that exists at each point (Potter, 2010).

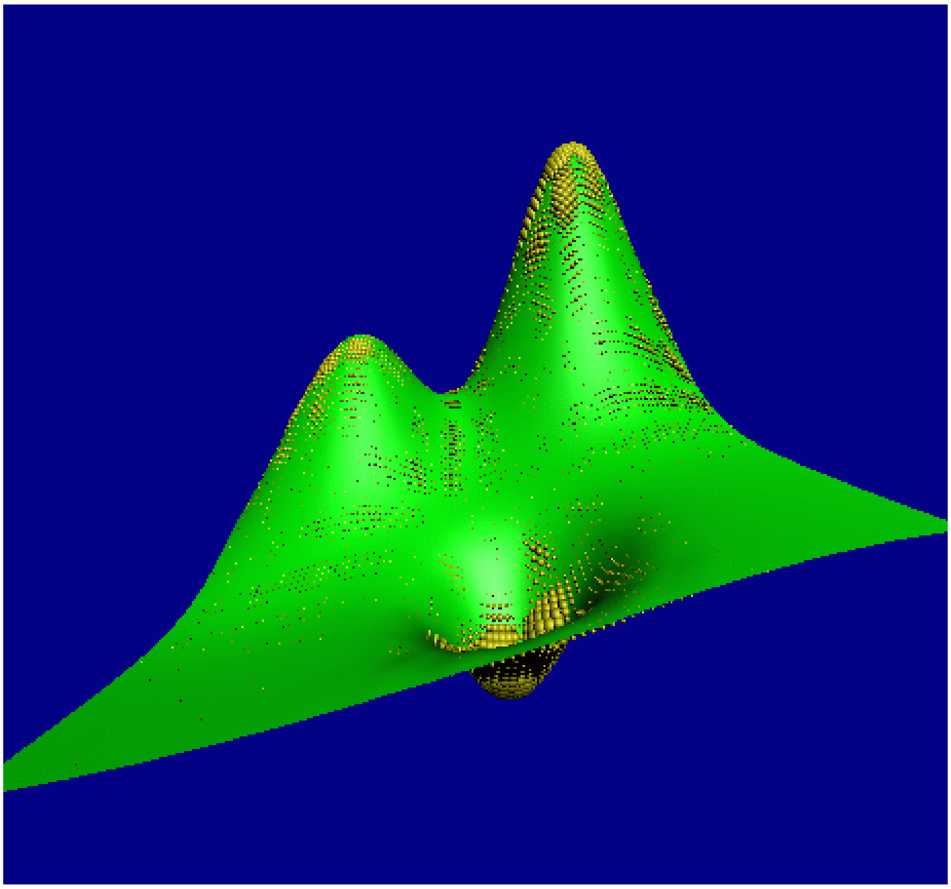


Figure 1: The spheres are centred on the data points and their size shows the size of the uncertainty. (Potter, 2010)

2.2 Sources of uncertainty

There are many possible sources of uncertainty that arise from the quality and consistency of data sources. Reveiro (2007) suggested that several different errors and uncertainties in a generic information system can be introduced at different stages of a visualisation pipeline. This pipeline is broadly divided into three stages: data acquisition, data transformation and data visualisation as shown in Figure 2.

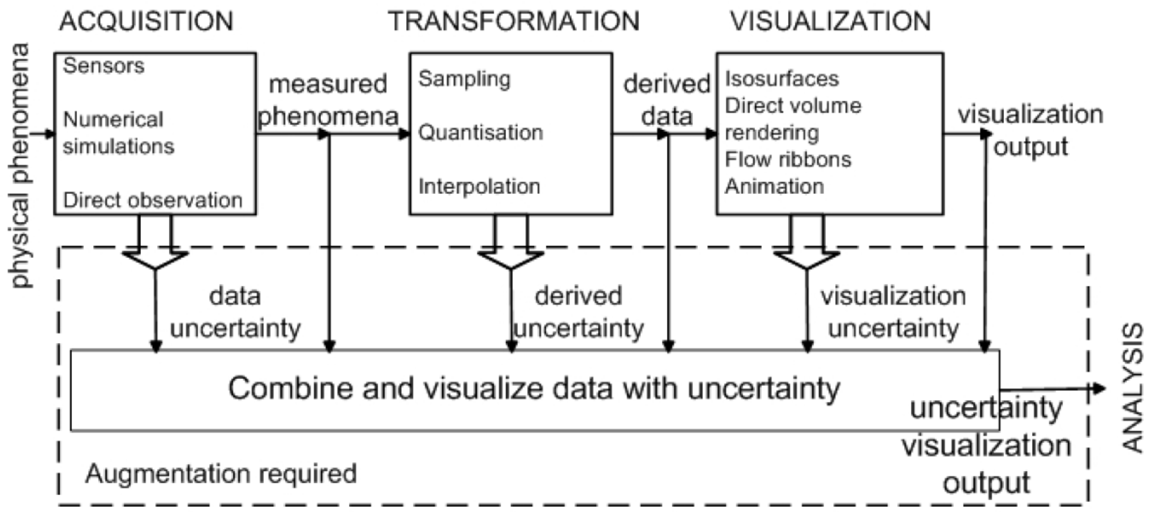


Figure 2: Visualisation pipeline representing the introduction of data uncertainty from the model and measurements (acquisition), derived uncertainty that results from the transformation of the data, and visualisation uncertainty that results from the visualisation process itself (Riveiro, 2007)

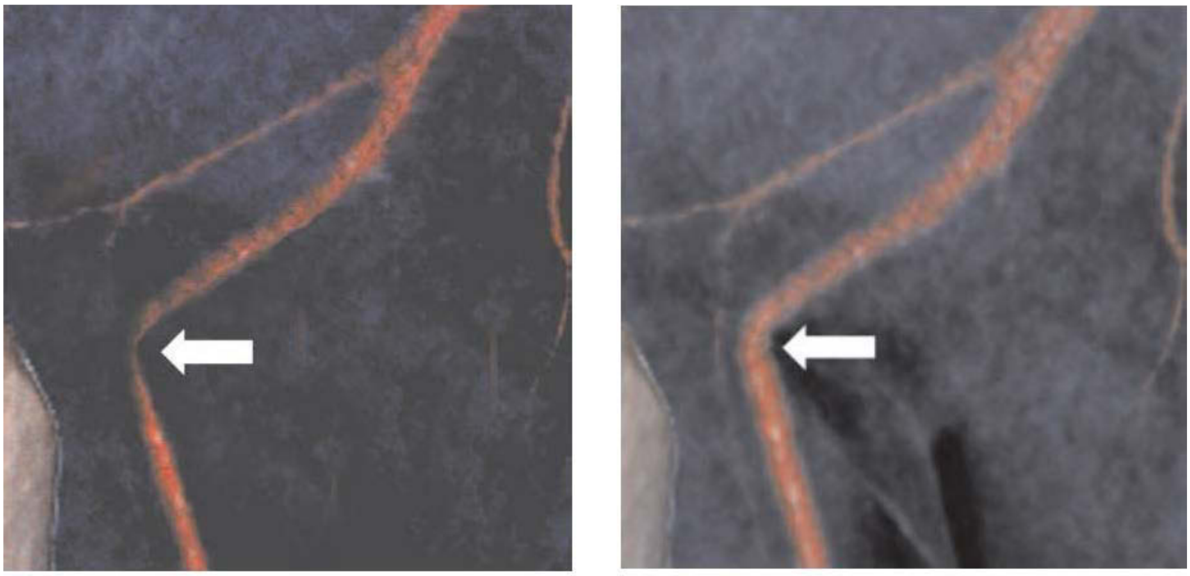
Uncertainty can be introduced at any stage of this pipeline from acquisition to visualisation as follows:

- **Data acquisition stage**
  Uncertainties occur from the models used and the measurements made at the time of acquisition. For example, uncertainty could arise when: the sensors have limited resolution; their readings contain noise; their measurements may be uncertain due to miscalibration; and sampling is sparse in time and space.

- **Data transformation stage**
  In most cases, raw data is not directly rendered without further transformation. Numerical calculations, for example, can introduce errors from the limited precision of numerical integration algorithms, or distortions can be introduced that amplify some features and de-emphasise others. The process of converting raw data into a suitable form may involve: normalising, non-linear scaling, averaging; interpolating; resampling; and quantising. Note that these transformation operations may occur as early as the data acquisition stage or as late as the visualisation stage.

- **Data visualisation stage**
  Visualisation itself can be a source of uncertainty. In this case, uncertainty is generally associated with the rendering models and algorithms used to generate the visualisation. For example, rendered 3D scenes will appear different when different radiosity algorithms are used to determine the global illumination (Arvo et al., 1994). Similarly, different approaches to direct volume rendering of 3D data sets could yield different results (Möller et al., 1996). One good example is

illustrated in Figure 3 (Lundstrom et al., 2007). An artery is shown in (a) which appears to be blocked and in need of surgical intervention. However in (b), by simply changing visualisation parameters, the artery now appears to be healthy.



(a) (b)

Figure 3: Uncertainty from visualisation is illustrated in this example showing a possibly blocked artery (a), or unblocked artery (b) using different visualisation parameters (Lundstrom et al., 2007).

2.3 Discussion

There have been many other efforts to classify the sources and types of uncertainty. New types of uncertainties are encountered by analysts as new ways of processing data are developed. There are also additional concepts of uncertainty that have been suggested, such as: fuzziness; plausibility; belief; or necessity (Yao et al., 1995, Griethe and Schumann, 2006). As uncertainty becomes more abstract, it becomes more difficult to represent, but it may also have less relevance to data visualisation. In the following chapters we will focus primarily on those types of uncertainty relevant to data visualisation and decision making.

The nature of the uncertainty associated with the data discussed in the previous sections determines how it needs to be represented. In the next chapter we will discuss some of the visualisation approaches used to help analysts and decision makers manage and understand imperfect information.

3. Uncertainty Visualisation Techniques

3.1 Background

There have been many attempts to categorise the approaches used for uncertainty visualisation. Gershon (1998) proposed two general categories of uncertainty visualisation techniques: intrinsic and extrinsic. Intrinsic representation techniques integrate uncertainty in the display by varying an object's appearance, for example by varying visual variables such as texture, brightness, hue or shape. Extrinsic techniques add geometric objects, including arrows, bars, and complex objects (such as pie charts) to represent uncertainty.

Pang et al. (1997) simply categorised uncertainty visualisation methods into seven categories:

1. Add glyphs (icons) to the visualisation to represent uncertainty (e.g. error bars)
2. Add geometry to show the possible variation due to uncertainty (e.g. maximum and minimum curves in a data plot)
3. Modify geometry to indicate the degree of uncertainty in the geometry (e.g. using dotted lines for a curve)
4. Modify visual attributes of the data (e.g. changing the transparency of a curve):
5. Add animation to show uncertainty (e.g. blinking curves)
6. Add acoustic cues to indicate uncertainty
7. Add psycho-visual cues to indicate uncertainty (e.g. subliminal images could be show to provide alternative, but less likely, interpretations).

Davis and Keller (1997) suggested that representation techniques could be broadly categorised as either static or dynamic techniques. For example, the use of animation would be considered a dynamic technique, while the other categories would be considered as static techniques.

3.2 Uncertainty in geospatial contexts

Griethe and Schumann (2006) suggested five simplified and intuitive categories of visualisation for uncertainty in geospatial contexts as described in the following sections.

3.2.1 Utilisation of graphical variables

3.2.1.1 Colour

There have been many visualisation approaches described that use the HSV (Hue, Saturation, Value) components of colour to display uncertainty (See Figure 4). MacEachren (1992) considered colour saturation as "the most logical one to use for depicting uncertainty". He argued that information with a high level of certainty should be represented by pure hues, while less certain information should use a correspondingly less saturated colour (i.e. greying out uncertain areas to make their colour hue "uncertain").

However, as illustrated in Figure 4, the use of colour saturation has possible limitations in that colours with low saturation may be difficult to distinguish from each other (Brown and van Elzakker, 1993).

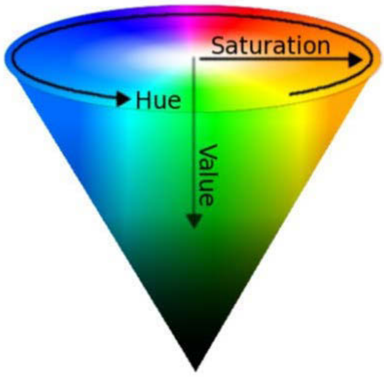
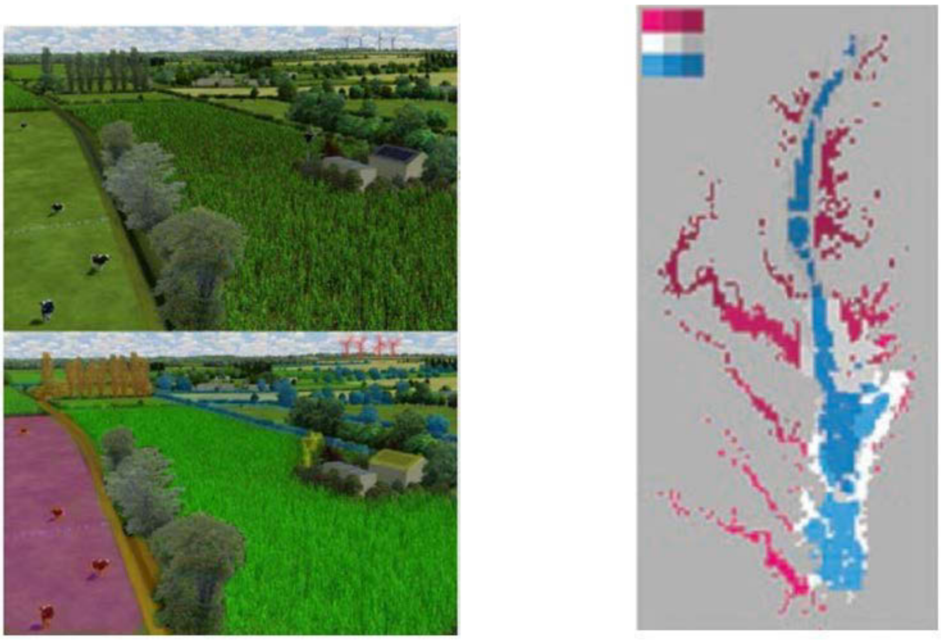


Figure 4 : The HSV cone from (Potter, 2010) shows how it is difficult to distinguish between low saturation colours.

Uncertainty can also be represented using the hue (H) component of a visualisation (See Figure 5). For example, a red hue could be used to represent higher uncertainty in a measurement, while blue could be used to represent lower uncertainty (Howard and MacEachren, 1996). A related approach is to simply use colour coding of data features to represent different levels of uncertainty(Appleton, 2004).



(a) *(b)*

Figure 5: (a) The usage of colour (hue) to encode uncertainty in the future development of a rural environment setting (Appleton, 2004) (b) Usage of bivariate representations that depict data (inorganic nitrogen in Chesapeake Bay) and uncertainty together using colour value (dark means more nitrogen) and hue (blue means more certain)(Howard and MacEachren, 1996)

Jiang et al. (1995) proposed a different HSV encoding system to represent uncertainty in fuzzy spatial analysis. In this approach, hue is used to assign nominal categories while saturation can confer data values, and lightness is changed to show uncertainty. (Dark areas have a higher certainty than light areas.)

MacEachren (1992) also considered that texture is the most appropriate approach to depict whether information is "certain enough" or "not certain enough". Davis and Keller (1997) suggested that colour hue, colour value, and texture are potentially the best choices for representing uncertain information using static techniques.

3.2.1.2 Focusing metaphor

MacEachren (1992) proposed a "focusing" metaphor that uses "out of focus" depictions for uncertain information and "in focus" depictions for certain information. He suggested using three graphical variables to depict uncertainty in this way: crispness, resolution and transparency. Crispness describes how easily different areas of the graphic can be distinguished, as shown in Figure 6(a) and 6(b). Resolution describes the significance of different features of the graphic, as illustrated by the different levels of pixelation shown in Figure 6(d). In his usage, transparency represents the level of fogginess applied to the graphic. A higher degree of fogginess is used to represent higher levels of uncertainty, as shown in Figure 6(c).

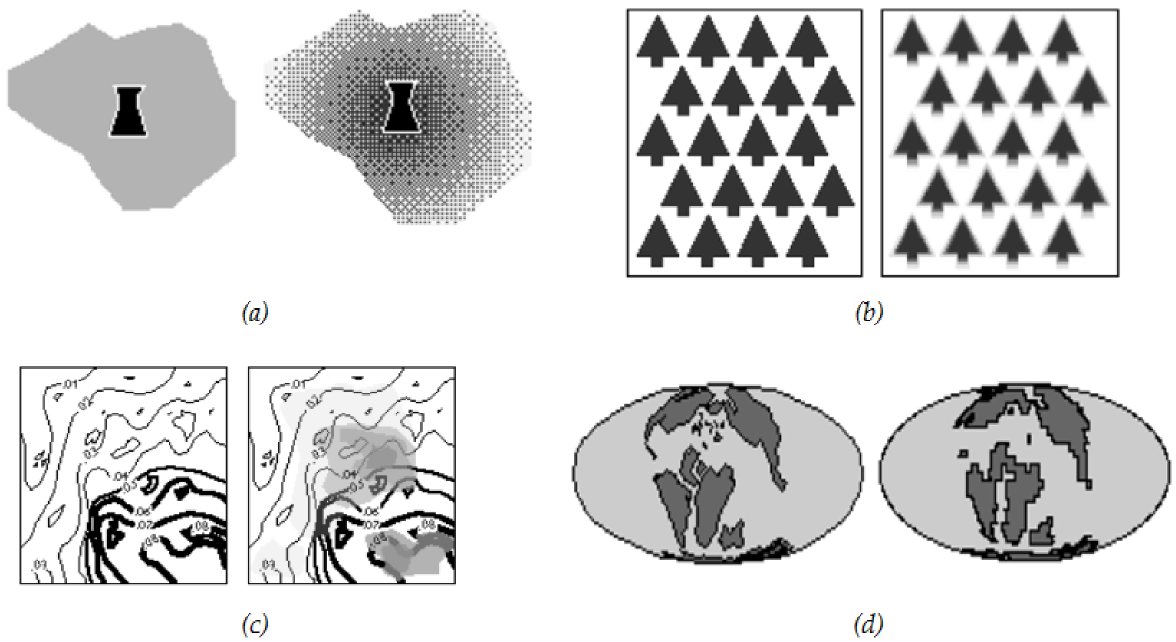


Figure 6: Uncertainty represented using different graphical variables (MacEachren, 1992): (a) The depiction of a risk zone around a nuclear power plant showing certainty vs uncertainty using contour crispness; (b) The depiction of land cover type showing certainty vs uncertainty using less crisp symbols or glyphs; (c) The depiction of ecological risk due to ozone showing certainty vs uncertainty using levels of fogginess ('transparency'); (d) The depiction of geography showing certainty vs uncertainty using pixilation.

Similarly, Brown (2004) argued that mapping the uncertainty to a colour map as a feature does not produce an immediate "perception" of uncertainty in the data and it has to be "interpreted" via a higher level cognitive process. He suggested that "blurring" is the most immediate and intuitive metaphor for depicting uncertainty. As illustrated in Figure 7, blurring is the attenuation of the high spatial frequency details of the visualisation. By removal of the high frequency information in the visualisation, the viewer recognises the lowered confidence in that information.

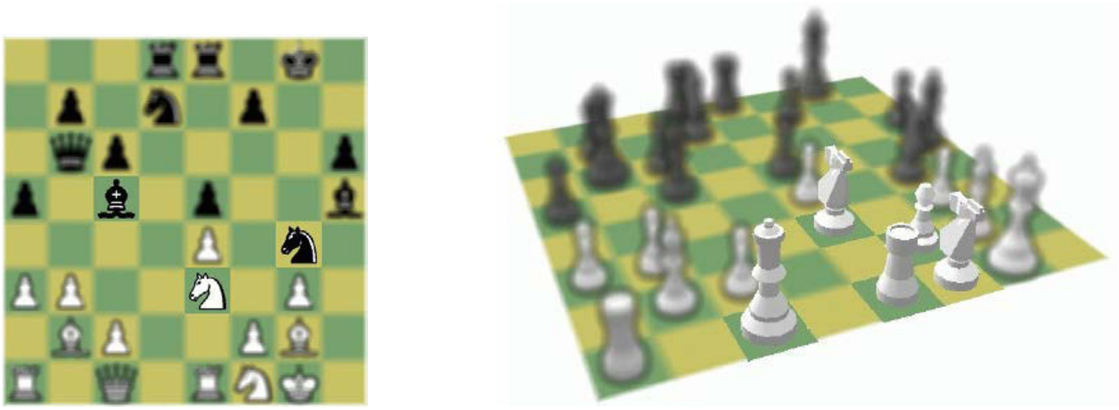


Figure 7: A chess tutoring system showing the chessmen that threaten (left) and cover (right) the knight on e3 (Kosara et al., 2001) using blurring. This effect could also be used to blur uncertain information in a visualisation.

Pang et al. (1997) suggested the use of a stereoscopic effect to generate blurring. With 3D stereo glasses, a 3D stereo effect is achieved by alternating the left and right images every frame to the left and right eyes. Blurriness could be achieved by showing two different images, or two identical images could be used to display a clear picture.

3.2.1.3 Opacity

In contrast to the "fog" effect in Figure 6(c), Drecki (2002) proposed an "opacity" method which utilised the transparency of the object to depict uncertainty. In this method, the highly transparent objects indicate high uncertainty, while opaque objects are considered certain.

Figure 8: The usage of transparency to encode uncertainty in medieval architecture (Isenberg, 1999)

Figure 8 illustrates a graphical reconstruction of a medieval building, depicting uncertainty about the architecture. While the foundations of the building are known and more clearly shown, the architecture of the building above the ground is less certain and so is represented using transparency.

3.2.2 Integration of additional objects

3.2.2.1 Glyphs

Another approach used to represent uncertainty is to map it to additional graphics such as glyphs, labels, contours, isosurfaces, etc. Glyphs are graphical objects in which multiple visual variables can be used to represent multiple data attributes. They are thus useful for representing uncertainty, especially multiple types of uncertainty (Pang, 2001, MacEachren et al., 2005, Sanyal et al., 2009). For example, to visualise uncertainty in wind and ocean currents, Pang (2001) represented uncertainty in direction and magnitude using different glyph attributes (see Figure 9). Pang (2001) also suggested that different types of glyph can be used to represent varying levels of uncertainty.

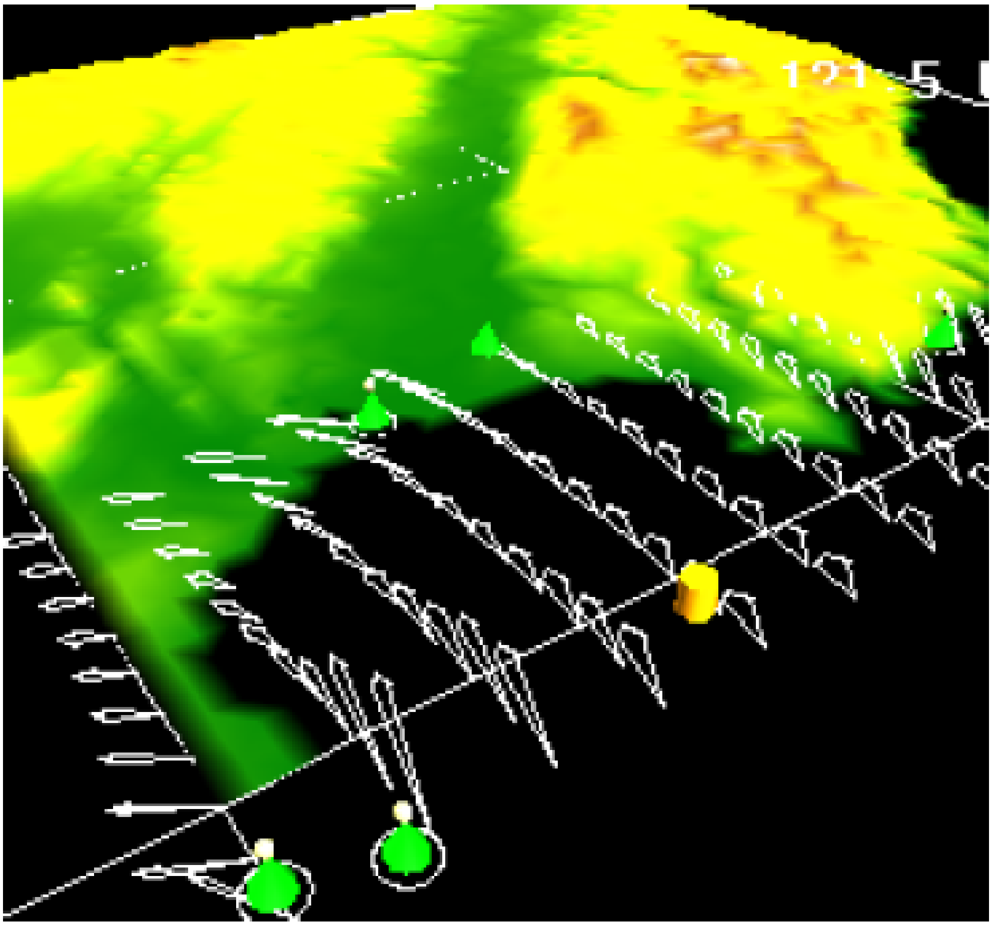


Figure 9: Glyphs indicating wind direction, magnitude and uncertainty. The width of the glyph head corresponds to angular uncertainty. (Pang, 2001)

3.2.2.2 Contours

Contour lines are a two dimensional visualisation technique widely used to show lines of equal value for a variable in three dimensional data. Uncertainty in contours can be represented by a variety of techniques. For example: by modifying contour colour (Osorio and Brodlie, 2008); widths (Dutton, 1992); and opacity (Zhang et al., 2010). In addition, spatial uncertainty can be encoded as the size of gaps in broken contour lines – the more uncertain, the larger the gaps (Pang, 2001).

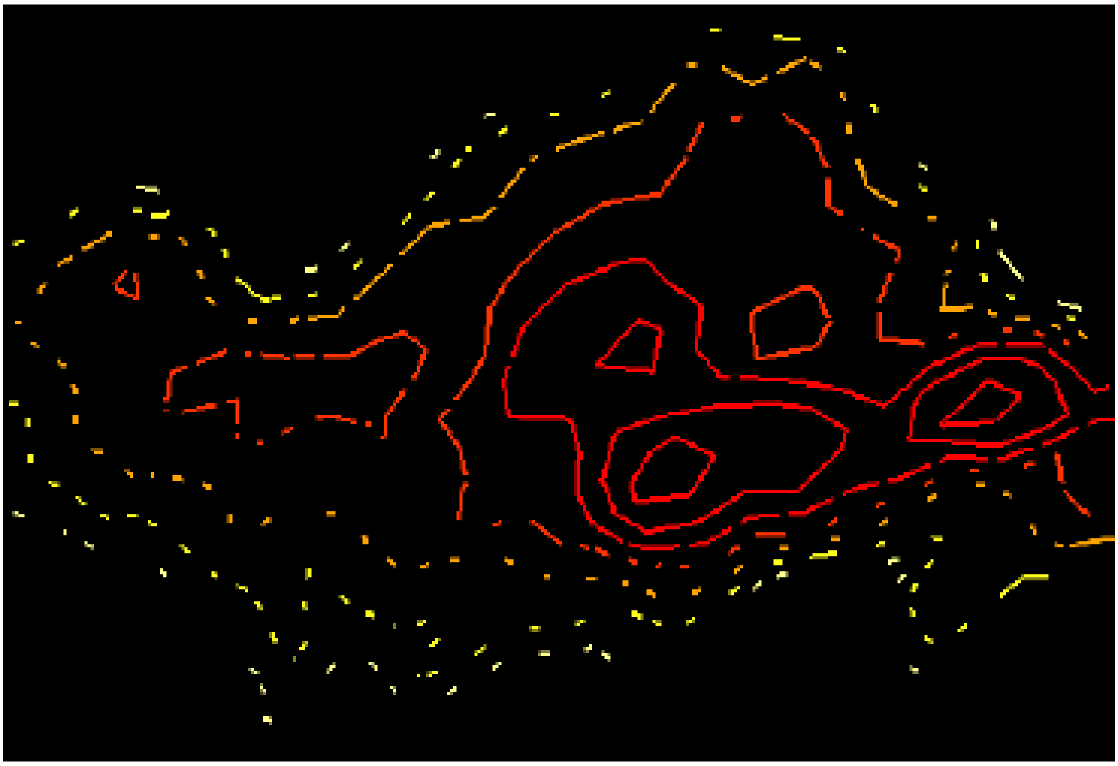


Figure 10: Example of uncertainty representation using broken contours. The larger gaps mean higher uncertainty (Pang, 2001)

3.2.2.3 Isosurface rendering

An isosurface is a three dimensional analogue of a contour line (or isoline) which represents surfaces of constant value within a volume of space. The conventional isosurface rendering applies a constant colour to isosurfaces, allowing different colours and textures to be used to represent additional information. For example, Rhodes et al. (2003) proposed uncertainty visualisation for isosurfaces using an additional texture mapped on top of the surface, with variations of hue and opacity of the texture to represent the level of uncertainty (see Figure 11).

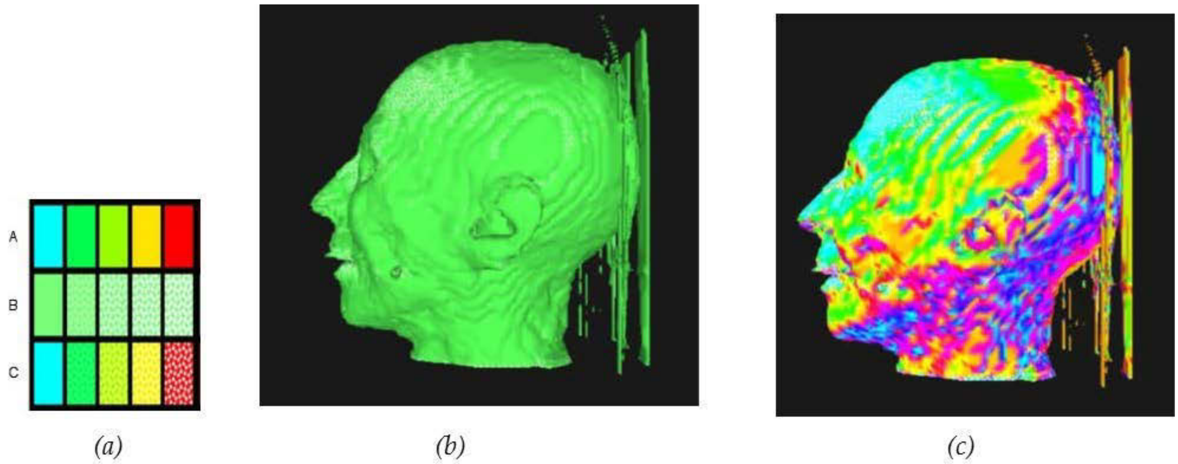
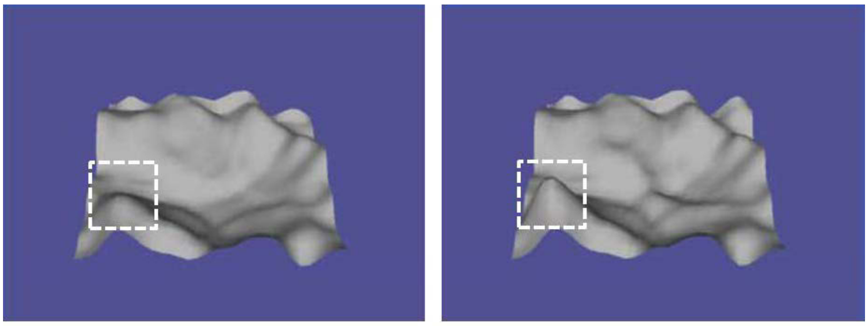


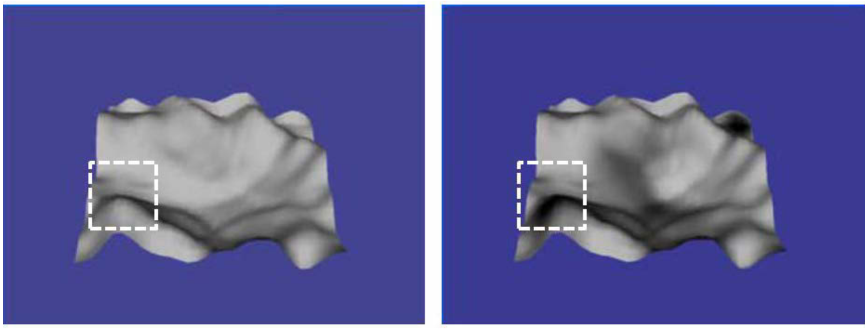
Figure 11: Different degrees of uncertainty in a medical domain are shown here using hue and texture. (a) Colour key showing example of A: Hue, B: Texture C: Hue+Texture (b) Uncertainty value mapped to texture opacity (with constant hue) (c) Uncertainty value mapped to hue and texture (Rhodes et al., 2003)

3.2.3 Animation

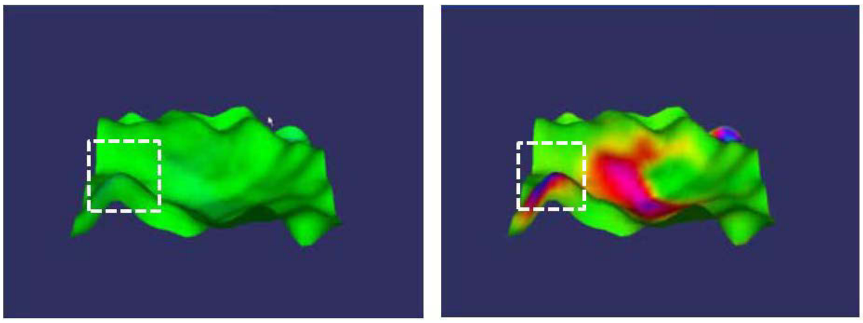
There have been many approaches which use animation to represent uncertainty. One way to represent uncertainty is to allow two values to exist in the same spatial location, with an animation oscillating between the two values. This provides a temporal mapping to uncertainty that could be used to show the range of possible values for data representing a continuous variable. Or, for categorical data, the degree of uncertainty can be depicted by changing the animation parameters such as duration, speed, rate of change, order and range or extent of motion. Fisher (1993) presented an "error animation" technique using a complex blinking effect. In his example, soil grids could belong to one of several possible soil classes represented by a particular colour. An animation was used where the colour of the soil grid rotated between the possible classes, with the dwell time mapping to the likelihood of that class. As illustrated in Figure 12, Brown (2004) implemented several uncertainty visualisation techniques for 3D terrain data, animating vertex height, surface luminance and hue.



(a) Frames from a movie of the vertex oscillation technique, with the changes in height values



(b) Frames from a movie of the luminance oscillation technique



(c) Frames from a movie of the hue oscillation technique

Figure 12: Uncertainty representations by the use of animation (Brown, 2004).

3.2.4 Non-visual techniques

One limitation of representing uncertainty visually is that it increases the dimensionality of the data, the richness needed in the interface (e.g. colour vs monochrome), and the visual complexity of the display. There have been many approaches using other modalities such as auditory and haptic cues. These avoid cognitive overload of the visual processing channel by using additional cognitive channels to interface with the computer system. Such multimodal systems have also been used to support attention management in data-rich environments where operators face considerable visual attentional demands (Sarter, 2006). For effective information delivery, these multimodal systems should be designed carefully with consideration of the user's cognitive system (Mayer and Moreno, 2002, Sorden, 2005).

3.2.4.1 Acoustic

Krygier (1994) suggested that uncertainty could be provided by incorporation of acoustic displays. For example, a sound map can be implemented to complement the existing visual map. The degree of uncertainty can be represented by a variable pitch, volume or rhythm that can be accessed by mouse interaction with the visual display, such as clicking and dragging. This presentation technique could be a solution to the problem of representing and comprehending uncertainty in an already crowded visual display.

Lodha et al. (1996) also introduced a system which allows the user to explore the dataspace using sonification techniques similar to those described above. However, a limitation of acoustic representation of uncertainty in this way is that it provides feedback on uncertainty at a point only, whereas a visual display gives a global view (Brodlie et al., 2012).

3.2.4.2 Haptic

Likewise, the use of haptic senses (e.g. touch or vibration) as additional modalities can enhance users' abilities to process more information simultaneously. Schmidt et al.(2004) combined haptic and visual approaches by mapping uncertainty to the haptic channel to complement a visual representation using glyphs. In this approach, they mapped the degree of uncertainty to the glyphs' degree of stiffness in a haptic channel. In this case, haptic devices (Immersion©'s CyberForce Grasp system) produced greater force feedback to user's fingers for larger values of uncertainty (see Figure 13). Since they applied the haptic channel only when necessary, this approach provides an intuitive understanding as to where the most prominent uncertainty lies in the data.

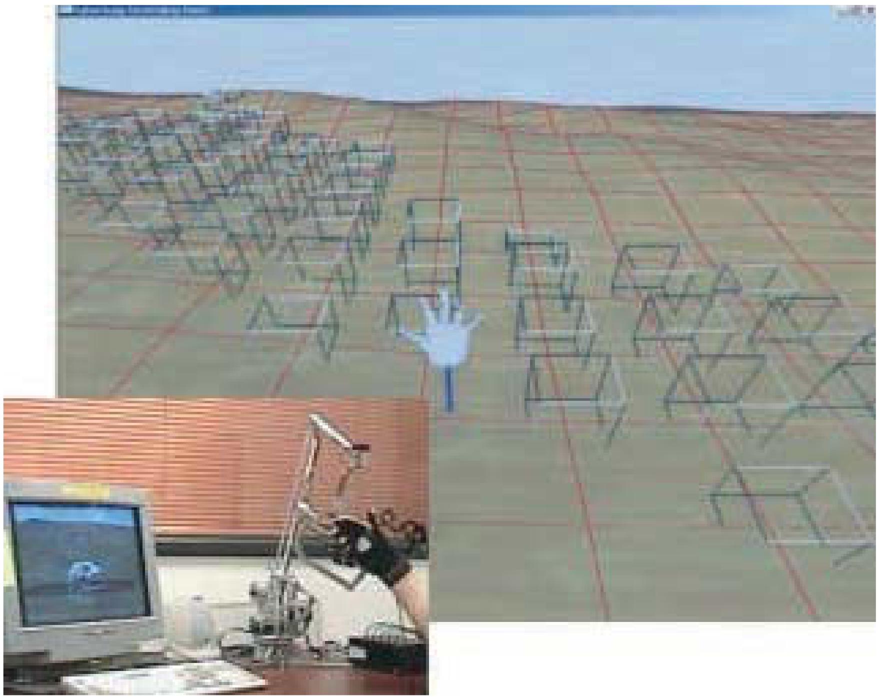


Figure 13: Haptic representation of uncertainty uses stiffness of the glyphs to convey uncertainty (Schmidt et al., 2004)

3.2.5 Interactive representation

Uncertainty can also be provided by other forms of user interaction. Wel et al. (1997) proposed a ”clickable map” where information concerning the uncertainty is not directly visible in the map but may be activated by pressing the mouse button at a pixel, providing a 'local' view of the data in a similar way to sonification and haptic feedback.

3.3 Evaluation of uncertainty visualisation techniques

User evaluations provide a systematic approach to understanding the usability of techniques and manipulable interfaces for using those representations (MacEachren et al., 2005). While most studies on uncertainty visualisation have focused on developing new technical applications and algorithms, little evaluation has been done on the effectiveness of their approaches. To empirically assess the effectiveness of proposed visualisation techniques, user studies with relevant participants should be included. Riveiro (2007) argued that most uncertainty visualisation research does not include a perceptual and/or cognitive analysis, or user evaluations that validate the usefulness of the proposed approaches. Similarly, Tory and Moller (2004) argued that only a few information visualisation designs utilised perceptual and cognitive theories, and this makes it difficult to systematically choose promising ideas for further study.

Kinkeldey et al.(2014), reviewed some of the evaluations of uncertainty visualisation techniques and grouped them into two categories: objective assessment and subjective assessment. Objective assessment includes tasks with measurable correctness of results such as value retrieval, ratings, comparisons or rankings. Whereas, for instance, subjective assessment includes: evaluation of the intuitiveness of an approach; the preference compared to other options; or the subjects' confidence in their responses when using it.

The following chapter discusses some of the relevant user studies on uncertainty visualisation for decision making tasks.

4. Decision Making with Uncertainty

The reliability of the information available to a decision maker influences the reliability of the decisions made. Indication of uncertainty in the visualisations provided to a decision maker is thus crucial to decision making (Deitrick, 2007). The information visualisation tools used by decision makers should make them aware of the presence, nature, and degree of uncertainty in the data, otherwise they may draw inaccurate conclusions, which could lead to costly mistakes (Olston and Mackinlay, 2002). Indeed, uncertainty visualisation has long been regarded as a difficult topic in C2 since the commander has to make decisions in a limited time frame with information that comes from varied sources, in many formats, with a continuum of validity (Summers et al., 2005).

The reliability of C2 decision making is affected by uncertainties in the sensor data, the possible interpretations of the situation that is developing, and on the degrees of freedom in the models used to evaluate the impact on the commander's intent. More work also needs to be done on the link between uncertainty and risk[3], such as investigating the influence of the uncertainty associated with the input variables of a model on the risk associated with decision-making (Brodlie et al., 2012).

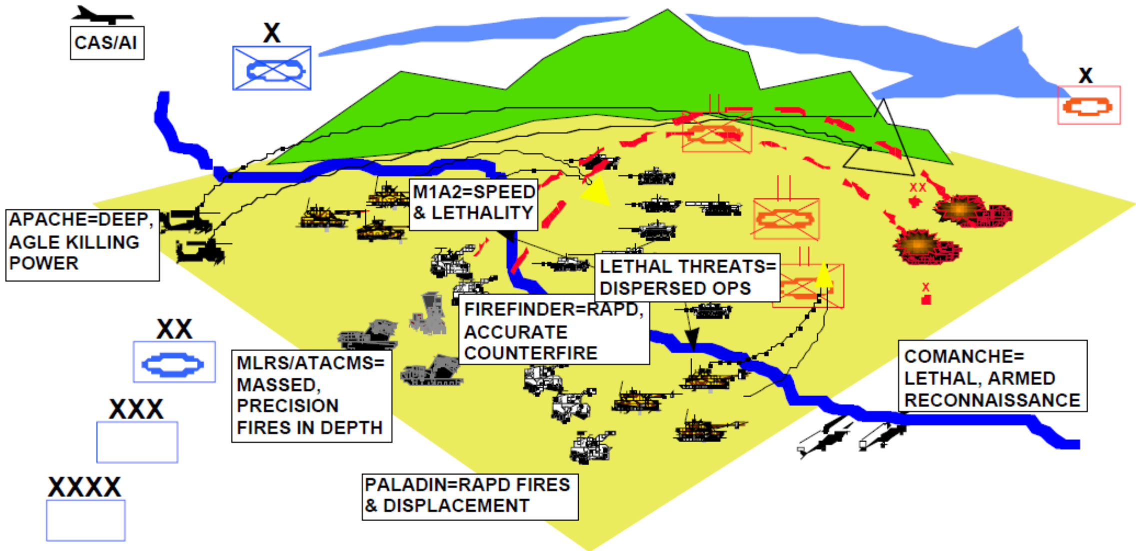


Figure 14: A hasty attack across a water obstacle requires complex reasoning about temporal, spatial, and categorical uncertainties (James et al., 1999).

[3] According to NATO Code of Best practice (NATO 2004. NATO Code of Best Practice for Command and Control Assessment *RTO TECHNICAL REPORT TR-081*.), "risk" is defined as the possibility of suffering harm or loss and "uncertainty" is defined as an inability to determine a variable value or system state, or predict its future evolution

4.1 Information fusion systems with uncertainty

Commanders are expected to maintain situation awareness of the battle space so they can make time critical decisions in a complex, uncertain, and ever-changing environment. They are increasingly being required to conduct new types of missions and operations other than war. These require a wide diversity of information, including troop positions, readiness data, human intelligence reports, cultural factors and political drivers. To successfully conduct a campaign, commanders need to assimilate large amounts of data, from a wide variety of sources, in limited timeframes. Yu et al.(2004) argued that attempts to simply bring more information to commanders are doomed to failure due to cognitive overload. As discussed previously, displaying massive amounts of data without consideration of human-computer interface (HCI) efficacy can potentially obscure critical information and degrade the effectiveness of the system (Chambers et al., 1983), resulting in loss of the decision maker's situation awareness.

Situation awareness can be defined as *'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'* (Endsley, 1995). Information fusion systems seek to improve situation awareness by reducing the cognitive load on the decision maker. Information fusion systems automatically or semi-automatically process and reason about large volumes of information from multiple sources (Bossé et al., 2007, Blasch et al., 2012). The decision maker(s) can be considered to be an integral component of these systems, handling those tasks that are too problematic for machines (Lambert, 2009).

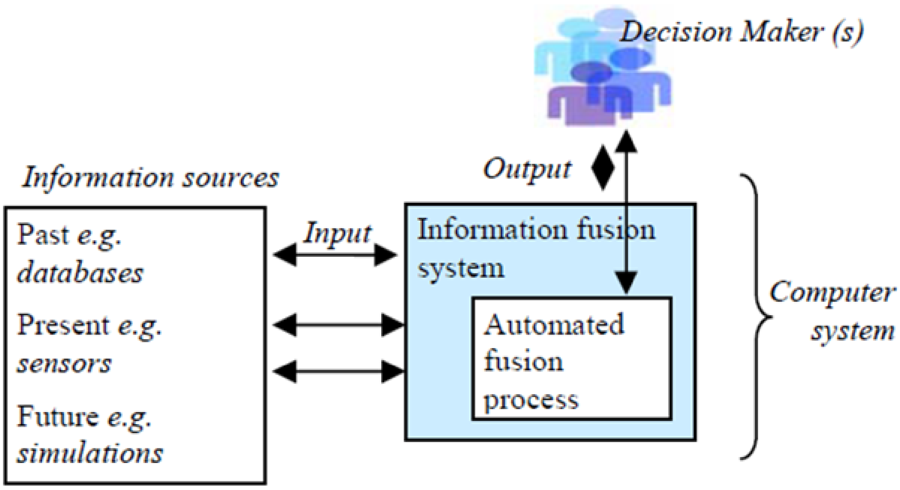


Figure 15: A schematic view of information fusion systems (from (Nilsson et al., 2008))

The standard JDL model for information fusion systems conceptualises information fusion as a four[4] level process in which different types of information are processed and different types of outputs are obtained:

- **Level 1:** *Object assessment*, in which sensor detections or entity features are fused to estimate the state of an object.
- **Level 2:** *Situation assessment*, in which the states of objects are used to estimate the relations between them, and hence the evolving state of a situation.
- **Level 3:** *Impact assessment*, in which the evolving situation is used to estimate likely scenarios, and make predictions about the impact of these scenarios on the decision maker's intent.
- **Level 4:** *Process refinement***,** in which the outputs of a processing stage are used to refine the estimation process at one or more levels. This is not a separate processing stage per se, but is integrated with all levels.

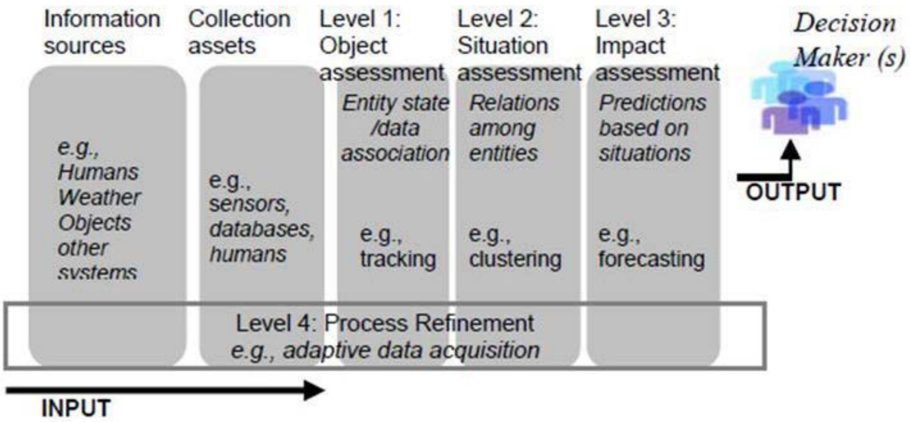


Figure 16: The standard JDL model of information fusion (from (Nilsson et al., 2008))

A key element of information fusion systems is the appropriate representation of the information used to guide the decision-making processes (Nilsson et al., 2008). A single data representation is not appropriate for all of these levels, and different techniques are needed for machine processing at each level. As discussed in Chapter 2, some degree of uncertainty is almost always included in the information sources and the processing stages. In this case, the decision maker may need to be aware of the nature and the degree of uncertainty in the displayed information at each level, and a different representation may be required for this. Summers et al. (2005) argued that situational awareness, and the opportunity for decision superiority, is increased when relevant data is effectively presented in a timely manner with a level of confidence. Information fusion systems which appropriately convey uncertainty, particularly its degree and its nature, may thus be critical to allowing the decision maker to comprehend the situation and project consequences into the future (Riveiro, 2007).

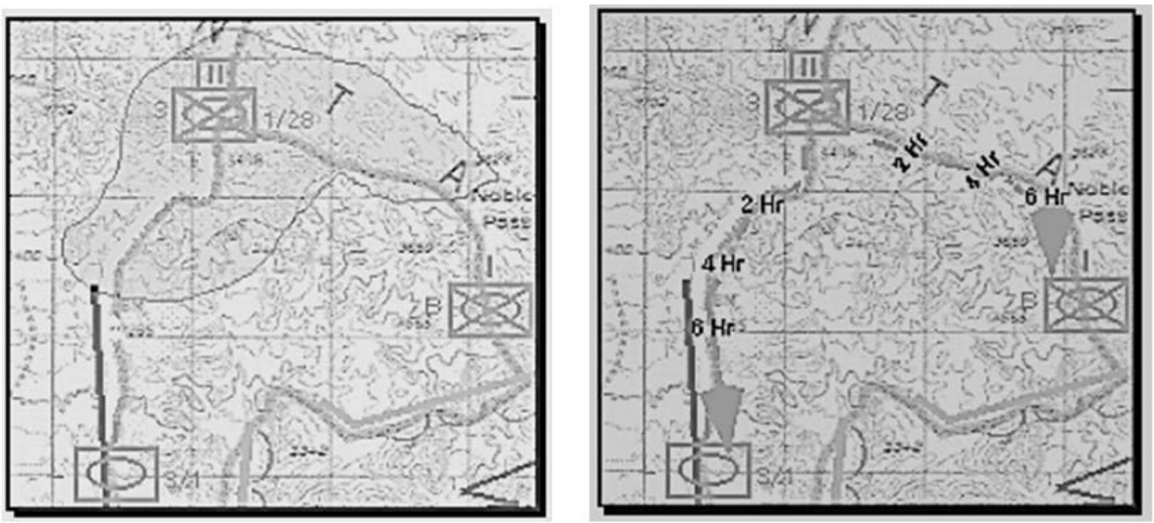
[4] A 5th 'Level 0' fusion stage is often included in which sensor (or other) signals are fused to produce a sensor detection above some background or noise threshold, but this level of processing is rarely displayed to an operational decision maker.

4.2 User studies

As discussed in §3.3, only a limited number of studies have been done on the effectiveness of different approaches for uncertainty visualisation in decision making. This section discusses the impact of uncertainty, different uncertainty representation techniques, and user experience on decision making.

4.2.1 The effect of uncertainty on situation awareness

John et al. (2000) conducted two experiments to investigate the effect of uncertainty on battlefield situation awareness and decision making. Their first experiment examined how different representations concerning the enemy's intent affect the situation awareness in a ground battlefield situation. Based on the assumption that better situation awareness will lead to better understanding and recall of the enemy's location and improve predictions of their future movements, experiments were conducted with marines who had experience working in the combat operation centre (COC). They showed that two graphical representations (arrows and blobs – see Figure 17) of enemy intent provided significantly better recall of relative direction and distance of enemy future position than the baseline without any representation, which required them to infer this from other information.



(a) (b)

Figure 17: Graphical representations of uncertainty in future enemy position (a) blobs: enemy's expected location in 6 hours in a boundary (b) arrows: expected movement of enemy in future (in 2, 4 and 6 hours)

Their second experiment explored the effect of situation uncertainty on the time required to make a decision. Three different levels of uncertainty concerning enemy's position and capabilities were applied to tactical decision games. Participants were divided into two groups according to their level of tactical decision making experience. The results revealed that the decision times for experienced participants were not affected by the degree of uncertainty concerning enemy strength and position; however inexperienced participants were more likely to choose to wait before acting when uncertainty was high.

This conclusion was validated by Kobus et al. (2001). In this study, uncertainty was not visually represented but was introduced through ambiguity in scenario. Their experimental subjects consisted of 52 marines who had high or low command post experience. They were split equally into two groups that participated in a virtual command post scenario that depicted a land warfare engagement and battle. One group began the scenario early, when uncertainty in the situation was high and reconnaissance reports were not yet available, while the other group began the scenario later when uncertainty was lower but an engagement was imminent and decision making time limited. Thus, this experiment investigated decision making with a 2 (uncertainty) × 2 (experience) factorial design (N=52). Their results revealed that the experienced participants were faster than the inexperienced group at executing a course of action early in the scenario when uncertainty was higher, but were not faster than the inexperienced group at making tactical decisions later in the scenario when the uncertainty was lower and time pressures were higher. However, perhaps not surprisingly, the more experienced participants were significantly more accurate than the less experienced participants at developing an appropriate course of action.

4.2.2 The effect of colour on decision making

Leitner and Buttenfield (2000) conducted an experiment that explored the effects of colour value, saturation and texture as the means of depicting uncertainty on maps. He looked at the time (response time for selection), accuracy (the correctness of location), and confidence (confidence level in the decision) of users of a spatial decision support system. Participants were asked to use a map to make site decisions for a conservation area (easy decision) and an airport (difficult decision) in wetlands, based on a set of predetermined planning criteria. Their results were compared with the site locations chosen by subject matter experts. The authors found that the addition of uncertainty information using texture (finer texture mapped to less uncertainty) or colour value (lighter colour mapped to less uncertainty) significantly improved performance for the easy decision, but no such difference was observed for the difficult decision. This may indicate that for decision making, the difficulty of the task could be the dominant factor compared to the uncertainty representation technique.

The user's response time and confidence in the decision made seemed to be similar with and without uncertainty representation. From this the authors conjectured that the techniques used for visualisation of uncertainty did not, on balance, clutter the map display.

Colour saturation was not found to be particularly effective in this study, which is consistent with other studies (Drecki, 2002, Sanyal et al., 2009, MacEachren et al., 2012). In particular, transparency has been found to be a more effective method of uncertainty representation than colour saturation (Newman and Lee, 2004). However users have been found to still have a preference for colour saturation, regardless of its low performance (Drecki, 2002).

4.2.3 The effect of animation on decision making

Aerts et al. (2003) implemented SLEUTH (Slope, Land use, Exclusion, Urban extent, Transportation, and Hill shade), an urban growth model designed to aid land use planning. SLEUTH used two uncertainty visualization techniques: static comparison and toggling. In their static comparison approach, a model of the result and its uncertainty were presented in side-by-side images, whereas in their toggled approach the result and its variations were sequenced in an animated loop (four frames per second). Participants showed a significantly higher confidence in their uncertainty estimation with the static representation technique than with the animation technique. They also showed a preference for the static technique. Interestingly, this finding seems to be supported by other studies that showed that dynamic techniques were less effective than static representations (Blenkinsop et al., 2000, Drecki, 2002).

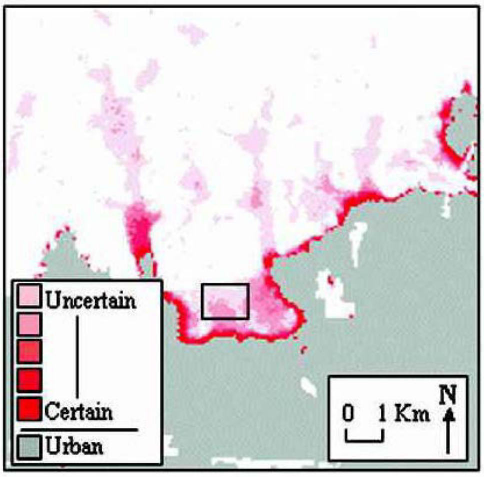
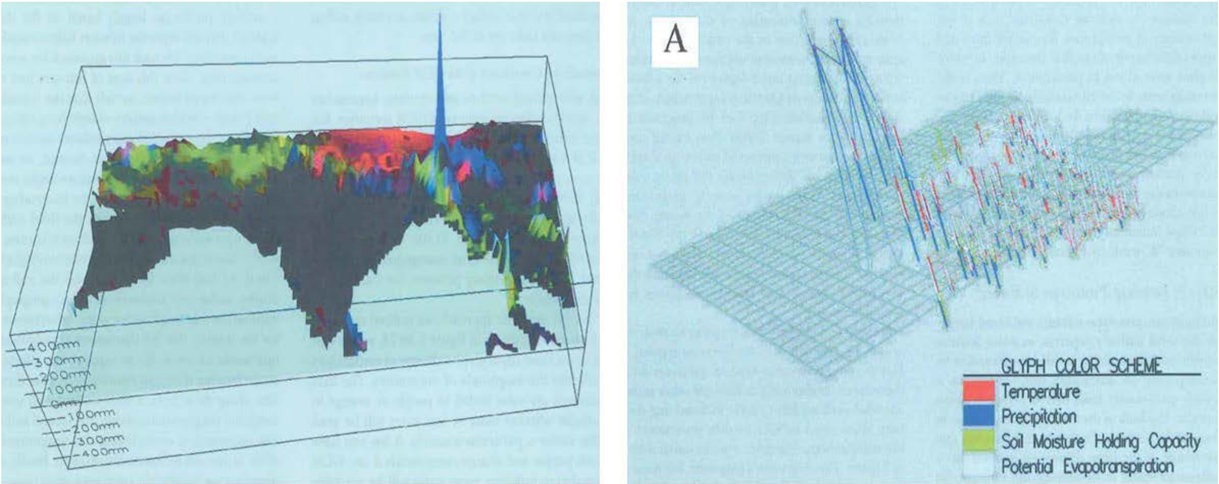


Figure 18: Uncertainty visualisation in SLEUTH using colour value (lighter means less certain area)

4.2.4 The effect of extrinsic representation (glyph)

Slocum (2003) studied the usability of their software tool for visualising future global water balance, which is a function of many uncertain factors. Two visualisation approaches for uncertainty were applied in their tool: intrinsic techniques using RGB and colour value; and extrinsic techniques using glyphs (see Figure 19).



(a) *(b)*

Figure 19: Visualising uncertainty of the future global water balance (a) Three-dimensional representation of surpluses or deficits in the model using RGB (R: temperature, G: Soil and B: Precipitation) with the colour value depicting uncertainty. (b) Usage of Glyphs to represent uncertainty associated with data (Slocum et al., 2003)

In developing the software tool, they utilised the principles of user-centred design and evaluation (Gabbard et al., 1999) which considered the importance of usability testing with actual task users during the design phase. Thus, during their software development, they conducted user tests with two expert groups: decision makers consisting of employees of the state government agricultural and water management offices; and subject matter experts consisting of civil engineers, atmospheric scientists, and geographers who were experts in water balance models.

User tests showed that the decision makers preferred the use of colour to depict uncertainty, whereas the subject matter experts preferred the use of glyphs. The authors conjectured that the intrinsic representation gives a better overview to allow decision makers to more easily see the 'big picture', and that the extrinsic representation provides better support for domain experts to do in-depth analysis. Based on these results, it can be concluded that uncertainty visualisation techniques should be adjusted to suit the task.

4.2.5 The effect of iconic representations on decision making for target classification

Finger and Bisantz et al.(2002) evaluated a variety of iconic representation techniques for visualising uncertainty in decision making tasks. In their first study they showed that subjects could appropriately classify five sets of icons to represent friendly or hostile targets, as shown in Figure 20.

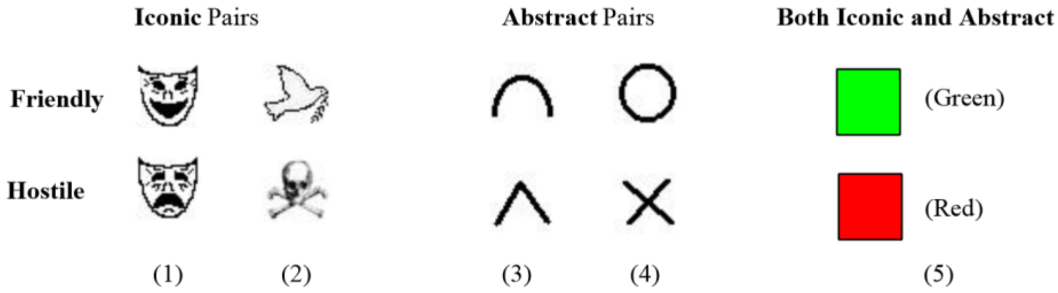


Figure 20: Icons representing object identity (hostile or friendly)(Bisantz et al., 1999)

They then showed that subjects were able to understand different levels of uncertainty associated with the identity of radar contacts as hostile or friendly using a series of 13 degraded and blended icons, as illustrated in Figure 21.

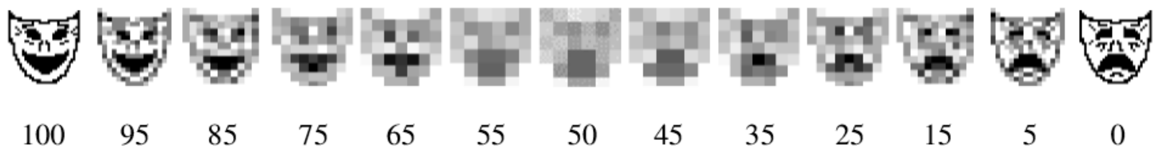


Figure 21: Icons representing a range of probabilities (hostile or friendly). The numbers indicate the probability of friendly (Finger and Bisantz, 2002)

They also looked at the use of degraded icons combined with a numerical probability estimate, as shown in Figure 22, and found that participants using only degraded icons show significantly better decision making performance than the other options.

Display Type	Example Stimulus
Degraded Only*	
Degraded with Probability	
Probability Only	

Figure 22: Example display stimuli for the degraded only, degraded with probability, and probability only display conditions (Finger and Bisantz, 2002)

4.2.6 The effect of uncertainty visualisation on target identification

Riveiro et al. (2014) presented an empirical study that investigated the effects of uncertainty visualisation on decision making in an air defence scenario where decision time is limited. As illustrated in Figure 23, they adopted semi-transparent filled circles to represent the uncertain position of tracks, and the thickness of the lines for the accuracy of scalar values such as altitude and range. In their experiment, there were 119 individual targets that required identification. Twenty two experienced air traffic operators, who were divided into two groups, with or without uncertainty visualisation, were asked to identify and prioritise targets that they thought were interesting or threatening. The results show that the group aided by uncertainty visualisations needed significantly fewer attempts to make a final identification and identified more hostile and suspect targets.

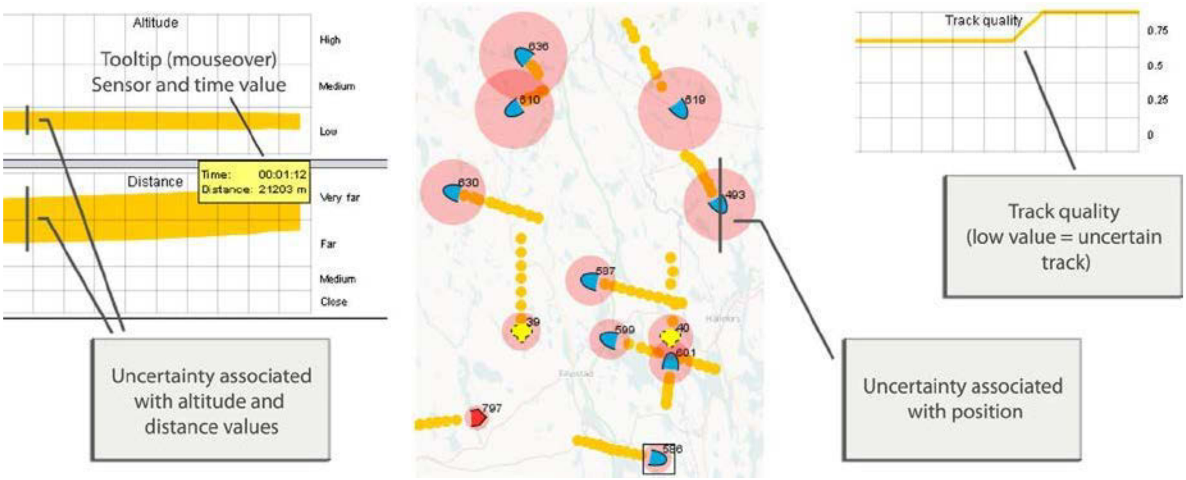


Figure 23: Uncertainty visualisation (Riveiro et al., 2014)

4.2.7 The perceived trust level of information in decision making

When decision support systems need to present statements about a situation, the uncertainty associated with such statements can be conveyed by using grading descriptors (e.g. unlikely, possible, probable and certain). However, these qualifiers could be easily ignored, or they may impose an additional cognitive burden on the decision maker. Smith et al. (2005) argued that the level of uncertainty can be conveyed by presenting the information using an appropriately trustworthy virtual avatar. They explored how the perceived trustworthiness of the avatar depends on facial attributes such as eye size, pupil size, face shape, forehead size, eye gaze and emotional expression (smiling, neutral and frowning) (see Figure 24). In this study, participants were asked to view all faces and assess the trustworthiness of each face on a seven-point scale ranging from "completely trustworthy"(1) to "completely untrustworthy"(7). Their results show that the facial characteristics of the avatar could potentially be used to control the confidence associated with the information delivered by an avatar.

In a follow-up experiment, participants were asked to rate their confidence in the advice from a 'trustworthy' avatar with the same advice presented as simple text. In this case participants considered that simple text is a more reliable source of information than an avatar. Based on these findings, the authors argued that different presentation modes could be used to appropriately convey different levels of reliability in the information presented.

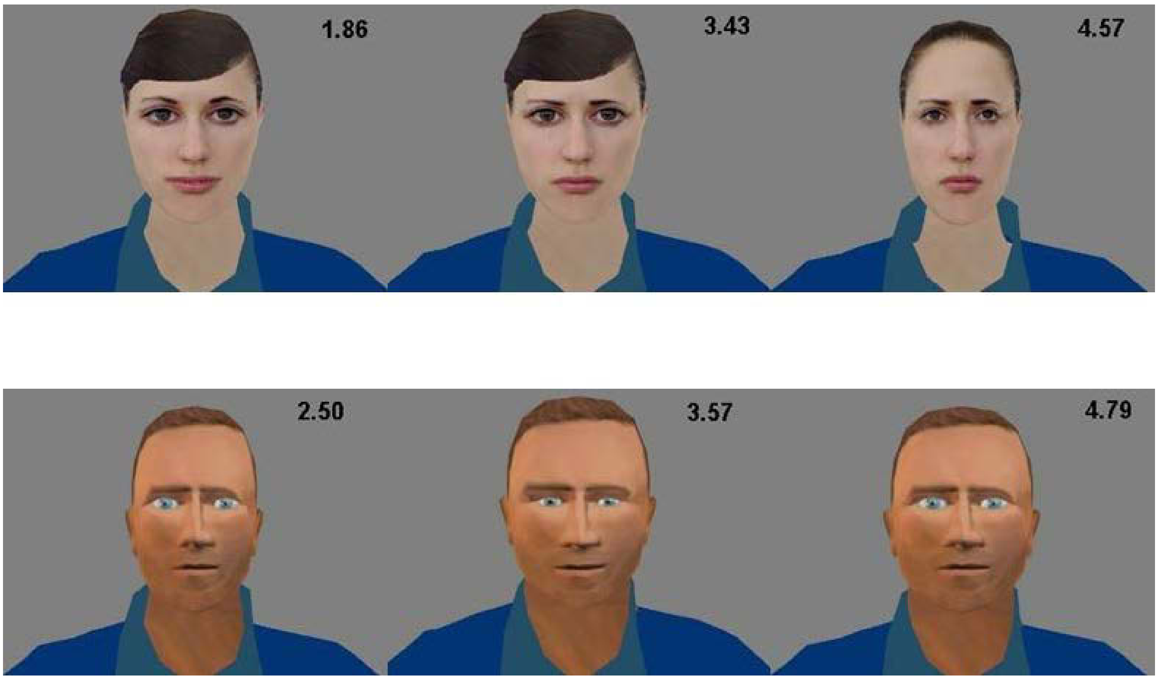


Figure 24: Examples of stimulus faces with trustworthy scores (lower score means higher trustworthy and vice versa)(Smith et al., 2005)

4.3 User issues

Empirical evaluation of uncertainty visualisation techniques is crucial to understanding the effectiveness of these techniques. Most of all, it is important to recruit relevant participants who are representative of the target user group in terms of age, skills, experience and so on. This is verified by studies which have considered the participants' level of experience (Kobus et al., 2001, Aerts et al., 2003) or domain of expertise (Slocum et al., 2003, Kobus et al., 2001, Aerts et al., 2003) as independent variables.

Similarly, Kinkeldey (2014) argued that many studies predominately recruited university students for their empirical studies due to their ready availability, and they often regarded students as domain experts. The author suggested that evaluation studies should provide additional training to allow unexperienced participants to gain experience with the scenarios, data, tasks or visualisation techniques for more effective empirical studies.

5. Guidelines for Uncertainty Visualisation

5.1 Graphical principles for visualisation

Several authors have proposed guidelines for data visualisation that encompass the requirements for uncertainty visualisation. For example, Tufte (1983) suggested two graphical principles that lead to good visualisation:

- Graphical excellence
  - avoid distorting what the data shows
  - give the viewer the greatest number of ideas in the shortest time with the least "data-ink"[5] in the smallest space
  - present a large amount of data in a small space
  - reveal multiple levels of detail
  - closely integrate the statistical and verbal descriptions of a data set
  - encourage comparison among the data.
- Graphical integrity
  - the representation of numbers should be directly proportional to the numerical quantities represented
  - clear, detailed, and thorough labelling should be used to defeat ambiguity and distortion;
  - show data variations and not design variations
  - the number of information-carrying (variable) dimensions depicted should not exceed the number of dimensions in the data
  - convincing graphics should demonstrate cause and effect.

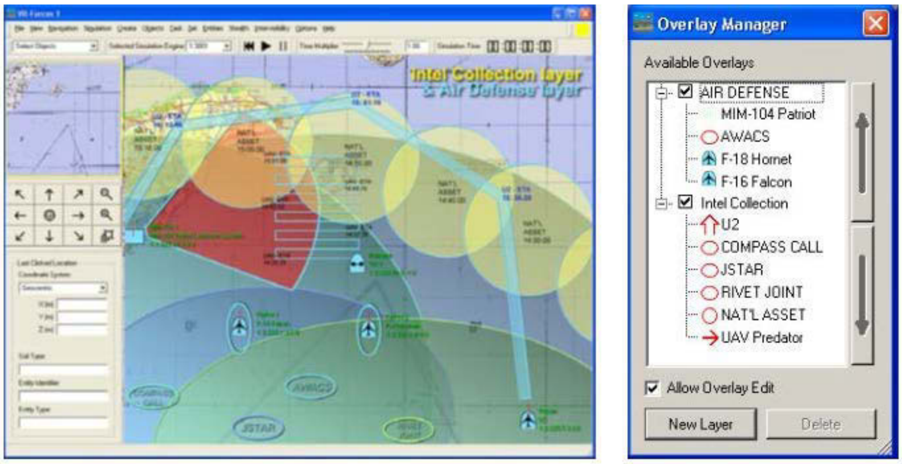
Tufte also proposed the "data-ink maximization principle" which claims that good graphical representations maximise data-ink and minimise the graphical components not conveying data directly (e.g. scales, labels and edges).

Summers et al. (2005) considered five key techniques for display management to increase situational awareness and decision superiority. These were implemented in a Tactical Ballistic Missile (TBM) defence prototype:

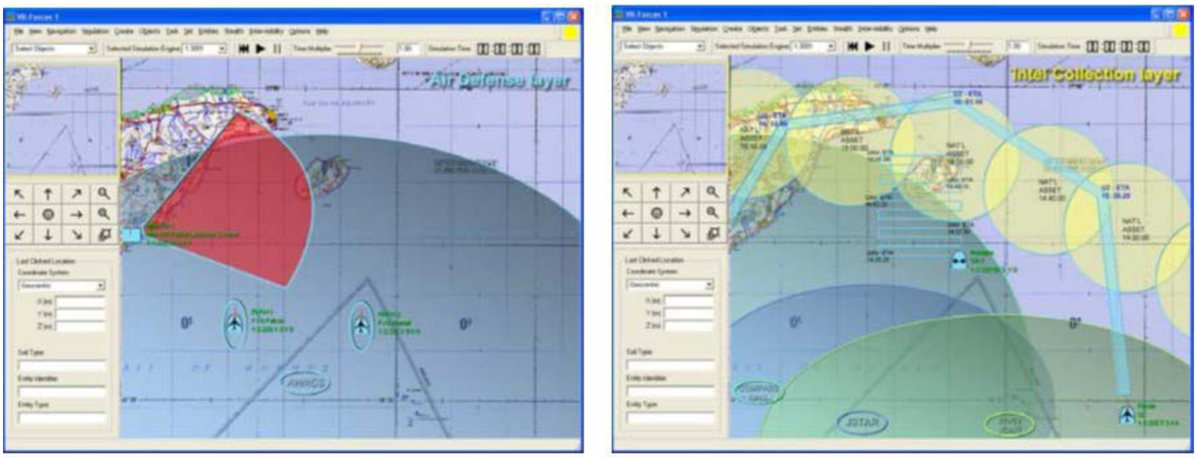
- **Tailoring the display:** to the situation, user's role, individual user preferences and screen size (e.g. hand-held, desktop or data wall).
- **De-cluttering:** focus on important information by providing the ability to filter out detail unnecessary to the task at hand. Techniques should interoperate with each other in a dynamic environment.

[5] Data-ink refers to the graphical components used for the representation of data.

- **Integration:** fluidly change visualisation techniques as the situation evolves.
- **Cross tool control:** all visualisation tools can show alternate views of the same situation, or views can be set and controlled by one for the others.
- **Use of toolkits:** to easily extend techniques and customized displays for re-use.



(a)



(b)

Figure 25: TBM prototype implemented using five key display management techniques (Summers et al., 2005): (a) Example of cluttered screen in which it is difficult to understand the situation. (b) Reducing clutter through overlay filtering makes the situation easier to comprehend.

As shown in Figure 25, the coverage of each system is placed on a separated overlay with different colours. Users can control the placement of each overlay on the display through an overlay manager which can create, toggle on/off and reorder individual overlays. By placing the display of these overlays under user control, users can avoid cluttering the battlefield map with unimportant information and enhance their situational awareness. In this example, the areas of coverage on an overlay are drawn as semi-transparent. From a pragmatic point of view, the author suggests that usage of transparencies for overlays provide a better user interface but renders more slowly on the display than other effects (e.g. patterned fills).[6]

Interestingly, Omodei et al.'s (2005) empirical study showed that decision making performance was degraded when participants were provided with more detailed information compared to the situation in which they were presented with less information. However, they assessed themselves as performing better. The authors conjectured that, under time pressure, more effort was spent gathering all available information than paying due regard to the important information, thus degrading their decision making ability. This result suggests that caution may be warranted when providing users with the option to navigate through or select different information displays or layers, including uncertainty representations, as it may degrade their performance.

5.2 Development strategies for uncertainty visualisation

Lapinski (2009) proposed an Uncertainty Visualisation Development Strategy (UVDS) which outlines a systematic approach with eleven strategies for designing an uncertainty visualisation, in the context their research supporting the Canadian Recognized Maritime Picture (RMP).

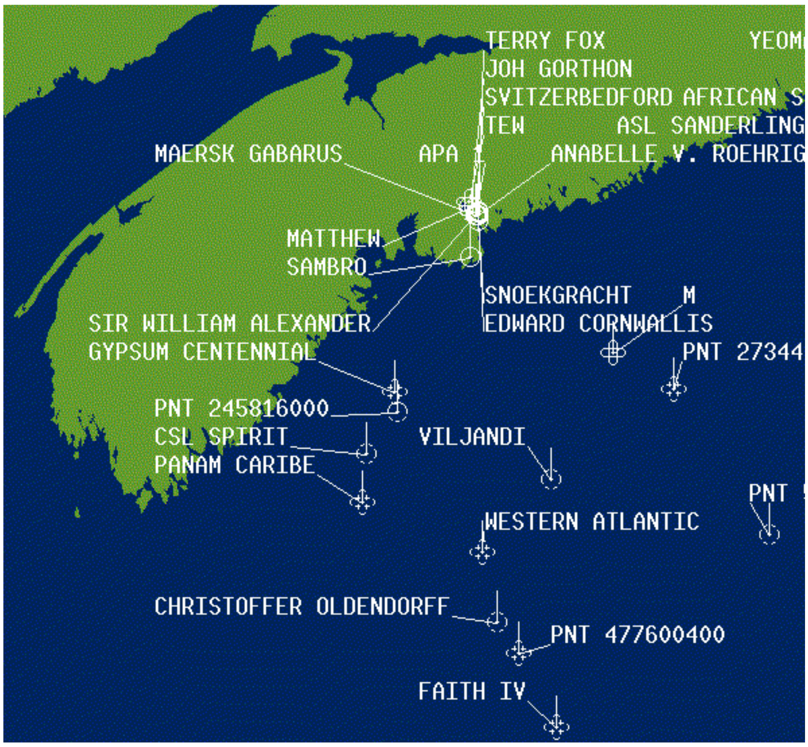


Figure 26: Unclassified example of the Canadian Recognized Maritime Picture (RMP) off the coast of Nova Scotia, Canada. The UVDS was applied to support the evolution of the RMP (Lapinski, 2009)

[6] This may no longer be a concern given improvements in graphical rendering technologies.

The stages of the UVDS are as follows (note: the author described that steps 4, 5, 6 and 7 in this strategy are interconnected and can therefore be completed in any order):

1. Identify the uncertainty visualisation task. This provides a high level generalised description of the task that can be phrased as a problem/mission statement.
2. Understand the data whose uncertainty needs to be visualised. This ensures that the person designing the visualisation understands the primary data to which the uncertainty is related.
3. Understand why uncertainty needs to be visualised and how the uncertainty visualisation needs to help the user. The intent and requirements of the audience need to be considered since the same data may need to be visualised differently for different audiences.
4. Decide on the uncertainty to be visualised. Since there may be multiple uncertainties associated with the data, the designer needs to recognise the uncertainties that could be visualised and then narrow these down to the uncertainties that should be visualised.
5. Decide on a definition of uncertainty. Increased understanding of the problem gained from previous steps will allow designers to define more appropriate definitions for the task. Lapinski (2009) reported that the designers feel more comfortable doing this step before step 4.
6. Determine the specific causes of the uncertainty. This step illuminates the many causes of uncertainty present in data and therefore the potential causes of the uncertainties the designers wish to focus on, which is important for the designer to understand.
7. Determine the causal categories of the uncertainty to illuminate the types of uncertainty the designer is dealing with. This information will be valuable when deciding how to visualise the uncertainty. Categories of uncertainty are related to issues of timeliness, precision, availability (missing or inaccessible), error (human or machine), and ambiguity (multiple meanings or interpretations).
8. Determine the visualisation requirements. The designer identifies the visualisation needs that address the problem/mission statement.
9. Prepare the uncertainty for visualisation. Do what is necessary to have the required uncertainty ready to be used in the visualisation. This could involve calculating uncertainty from collected data, transforming uncertainty measurements into the proper units, assigning uncertainty, extracting uncertainty from collected data, etc.
10. Try different uncertainty visualisation techniques.
11. Seek audience opinions and criticisms.

The author did not provide an empirical evaluation of this approach, however these guidelines could help the designer better understand the important concepts to be considered for uncertainty visualisation.

5.3 Challenges for uncertainty visualisation

In MacEachren et al. (2005), the authors reviewed several visual methods and tools for uncertainty visualisation and concluded their survey paper with seven core challenges that need to be addressed for uncertainty visualisation research:

1. Understanding the components of uncertainty and their relationships to domains, users, and information needs
2. Understanding how the knowledge of information uncertainty influences information analysis, decision making, and decision outcomes
3. Understanding how (or whether) uncertainty visualisation aids exploratory analysis
4. Developing methods for capturing and encoding analysts' or decision makers' uncertainty
5. Developing representation methods for depicting multiple kinds of uncertainty
6. Developing methods and tools for interacting with uncertainty depictions
7. Assessing the usability and utility of uncertainty capture, representation, and interaction methods and tools.

6. Uncertainty Visualisation for Joint Operations Command

6.1 Situational awareness for JOC

The situational awareness requirements of the Australian Defence Force's Joint Operations Command (JOC) range across the spectrum of ADF operations to achieve national strategic objectives. The users in JOC need to access, integrate and visualise a diversity of information across the Defence Enterprise including military text messages, unstructured documents, military databases and open-source content from civilian producers. Furthermore, these processes need to be tailored to support a variety of dynamic operational needs, because the users are unlikely to be subject matter experts in each of the data sets being integrated. It is crucial that they understand the uncertainties associated with the information being displayed so that they can mitigate operational risks.

Some specific use-cases of relevance to coalition operations in particular, but which are representative of the user requirements in general, are discussed below (Read et al., 2014).

6.1.1 Disaster response

In response to a natural or other disaster, the disposition and status of land, air, and maritime forces, the effective capability they can bring to bear, and their availability to respond, needs to be established. This potentially applies to not only formed units and deployed forces, but contingency forces as well. In addition, situational awareness is required of the disaster, its impacts on civilian populations and infrastructure, and the capabilities that need to be provided. This use-case applies at a national and an international level where ad-hoc coalitions, including defence forces, NGOs and OGAs, may be formed and reformed as required to meet emerging needs.

The types of information sources in this use-case include:

- **Open-source** – freely accessible from the internet but often poorly controlled. They can be provided by news services, government departments and NGOs, local governments, social media or other crowd-sourced content. They can, for example, contain information such as incident locations and areas of effect, geopolitical factors (international, national, local government), weather, civilian infrastructure, social networks and relationships.
- **Diplomatic** – usually sourced from government organisations and relatively well controlled. They can, for example, contain foreign policy, relevant treaties, protocols for dealing with NGOs, and international political considerations.
- **Emergency services** – usually sourced from government or affiliated organisations and relatively well controlled. They can provide information about emergency events and ongoing crises, available resources, capabilities and capability gaps.

- **Legal** – usually sourced from government organisations and well controlled. They can provide information about legal requirements and constraints, rights of access, legal response options and local laws.
- **Policy** – usually sourced from government organisations and well controlled. They can provide information about operating and communication protocols, information sharing constraints, and rules of behaviour.
- **Preparedness** – usually sourced from defence systems, well controlled and generally with a national security classification. They can provide information about the readiness and status of forces and their assigned roles.
- **Logistics** – usually sourced from defence systems, well controlled and generally with a national security classification. They can provide consumption & movement models and the composition of formed military units.
- **Capabilities** – usually sourced from defence systems, well controlled and generally with a national security classification. They describe the capabilities of military units and forces.
- **Operational** – usually sourced from defence systems, well controlled and generally with a national security classification. They describe the current tasking, location, status of deployed units and forces.
- **ISR (Intelligence, Surveillance and Reconnaissance)** – usually sourced from defence systems, well controlled and generally with a national security classification. In this use-case they would provide information about the disposition of national and coalition assets, civilian agencies, refugees and other civilians.

6.1.2 Search and rescue

This use-case has similar information requirements to the Disaster Response use-case above, except that the scope of the activity is much more tightly focussed, usually (but not always) on the recovery of a single group of people, vessel, or aircraft.

6.1.3 Maritime domain awareness

In this use-case, national and coalition capabilities may be involved in surveillance of sea-lanes and maritime approaches to identify unusual or suspect behaviour. This may be indicative of illegal or hostile activities, and JOC may be required to respond appropriately. The role of national and coalition military forces in this use-case may, in some instances, be to support the civilian law-enforcement organisations rather than take a lead role, and so may require access to information sources that are not managed by Defence.

The types of information sources required for this use-case are similar to those for the other use cases, and also include:

- **Law-enforcement services** – usually sourced from government organisations and well controlled. They can provide information about the status, locations, and capabilities of law enforcement agencies and assets;

- **Merchant shipping** – usually sourced from commercial organisations, or by proxy from law enforcement organisations. They can provide vessel itineraries, cargo & crew manifests and ports of call.

6.2 SAKI

SAKI (Situational Awareness Knowledge Infrastructure) is being developed by DST Group to explore the challenges of integrating information from diverse operational sources, and refine how that information needs to be displayed to meet different operational needs and roles. It allows JOC users to access and evaluate prototype capabilities from their desktops, using operational data sources. SAKI uses a layered service architecture as shown in Figure 27.

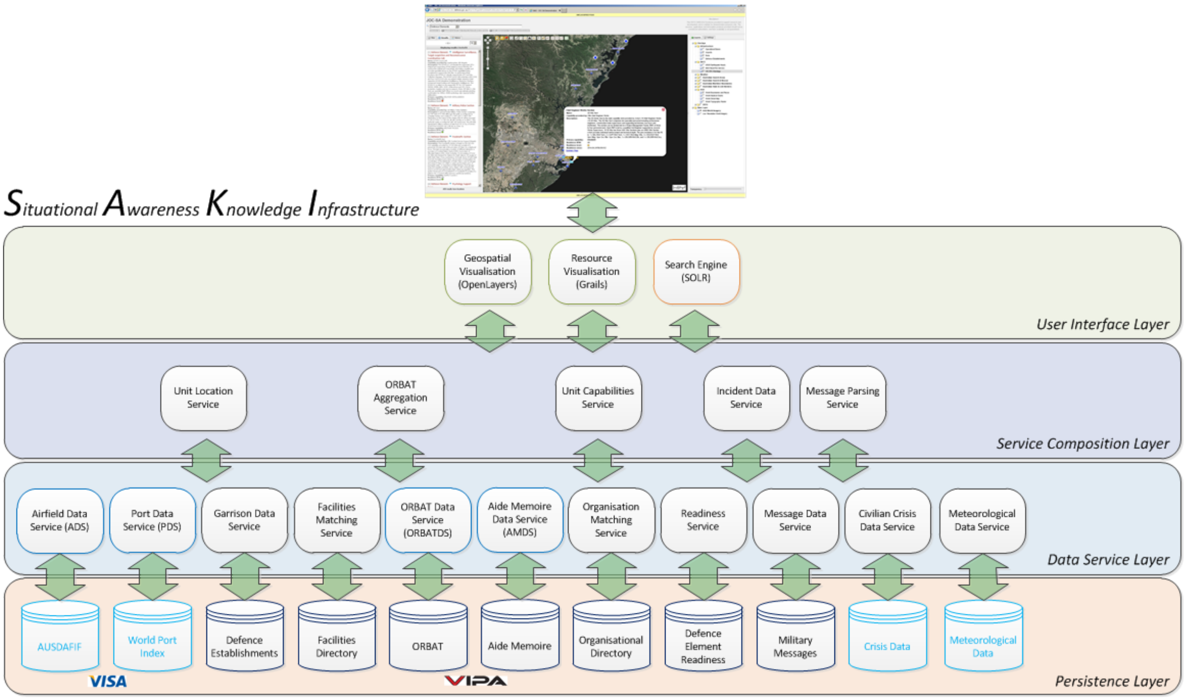


Figure 27: DST's SAKI system is being developed to identify and refine the ongoing services and visualisation requirements of Australia's Joint Operations Command (Read et al., 2014)

6.3 Sources of uncertainty for JOC

The sources of uncertainty for the SAKI system can be categorised using the 3 stages discussed in §2.2 (Riveiro, 2007), and are described in the following sections.

6.3.1 Acquisition

The main types of data sources used by SAKI, and indeed JOC, are discussed below. While this is not a complete list, it does capture the main classes of source and the types of uncertainties associated with these classes.

6.3.1.1 Military Text Format (MTF) messages

Military Text Formatted messages, originally developed to support teletext systems, still form the bulk of current military reporting systems, although they are currently transitioning to other, more flexible, formats such as XML. For this discussion we will focus on manually entered reports that are used to meet a variety of information requirements. The ADF currently uses the Mercury system to send these messages, which adds a header that provides handling and delivery instructions, and some additional information:

- DTG (Date Time Group): specifies when the message was sent.
- SIC (Subject Indicator Code): designates the operation and type of activity the message is about.
- Subject: A free text field that should provide a subject line for the message.

The body of the message contains a structured set of fields that usually include a free-text narrative in a semi-structured format, written by humans for humans. The writers make assumptions about common knowledge and context. This free-text narrative generally needs to be parsed to extract the information needed by the SAKI system.

The types of messages of primary interest to JOC are:

- BBXX voluntary weather observations from surface vessels.
- COMREP (Communications Report): contains information about changes to the communications circuits and networks.
- COMSTAT (Communications State): contains information about the communications circuits and networks to be used for the next 24 hours.
- INCREP (Incident Report): contains information about particular operational incidents, such as: location, time of incident, personnel involved, number of casualties, number of civilians involved, etc. Each incident report represents either a new incident or an update regarding a previous incident.
- INTREP (Intelligence Report): contains updates about the operating environment and actors within it, normally as a result of the IPB (Intelligence Preparation of the Battlefield) process.
- INTSUM (Intelligence Summary): contains a daily summary of the operating environment and actors within it.
- JJVV: contains bathymetric observations from surface vessels.
- LOCATOR: contains a positional self-report from a surface vessel at sea. Primarily contains structured data.
- LOCSTAT: contains the current location, and further intention or direction of travel of a (usually land) unit.
- LOGSTAT (Logistics Status): contains a report on the logistics status of a unit. This could be, for example, fuel or ammunition remaining.

- MISREP (Mission Report): contains updates on the progress or status of a mission assigned to a unit.
- OPREP (Operations Report): contains updates on the operational activities of a unit.
- OPSUM/OPSTAT (Operations Summary/Status): contains a daily summary of the operational status and capabilities of a unit.
- SITREP (Situation Report): contains situation updates from/for a unit.
- URDEF (Urgent Defect): contains a report on operational defects for a unit that may impact its ability to carry out its assigned activities or mission.

The types of errors that can occur when parsing these messages, hence leading to ambiguity in the content, are:

- Badly formatted text not adhering to the agreed standard, leading to parsing errors. In this case, a human operator may well be able to extract information from the message that a machine cannot, so the presence of this sort of error needs to be represented in some way.
- Poorly or incorrectly identified incidents or units, leading to incorrect assignment of reports to an incident or unit. While this may be a difficult situation to recognise, it may be useful to represent the closest known match for a unique id.
- Missing, erroneous (e.g. latitude and longitude values transposed), or incomplete (e.g. MGRS coordinates not specified to sufficient precision) location information. In some cases an intelligent system may try to correct for these errors, in which case this provides another potential source of unreliability that needs to be represented in some way.
- Missing or ambiguous date/time specification. In this case a reasonable default may be to use the DTG of the Mercury header, but this is a source of potential unreliability that may need to be represented in some way.
- Inconsistent or unknown named entities within the message body. This can lead to poor association of messages with events, situations, units, etc. While this may be a difficult situation to recognise, it may be useful to represent the closest known match for a unique named entity.
- Inconsistent information within a message, often due to transcription errors (for example, within a BBXX message). This inconsistency should be represented in some way.
- Corrections to MTF message are routinely broadcast, often leading to the removal or modification of previous messages. In this case, some form of representation that a correction has occurred may be required.

Network latencies may introduce a significant delay between the reported time of a MTF message and the time that it is available to the system as a ‘current’ update. This introduces a potential source of unreliability that may need to be represented in some way.

6.3.1.2 Open-Source RSS feeds

Rich Site Summary (RSS) and the similar Atom data feeds provide structured (XML) updates of information that is time-stamped and accessible to web applications. The information within an RSS update can be represented as free text or as (escaped) XML. In the case of free text, similar parsing issues and potential sources of uncertainty to MTF messages arise, the particulars of which depend on the individual RSS feed. In the case of XML content, consistency of the schema/ontology used is often problematic, even with a notional 'standard' being used, as different sources often interpret this differently. In this case, any inconsistencies between RSS feeds, or ambiguities in interpretation, may give rise to errors during the data transformation stage and may need to be represented or otherwise accounted for in some way.

GeoRSS is a particularly relevant XML schema used to represent geospatial content within RSS and atom feeds that comes in two variants: Simple and GML. Many of the data feeds of use to SAKI have a geospatial component represented using GeoRSS. While GeoRSS is a standard, how it is used to represent geospatial features is often not consistent. For example, a region affected by a bushfire could be represented by either a polygon or a closed polyline, or set of polylines. These use different GeoRSS data structures, so this distinction can be important when it comes to interpreting and/or representing the region.

Latencies of updates and corrections to RSS updates are possible uncertainties that may also need to be represented.

Finally, there are potentially many RSS feeds reporting updates to the same data, or replicating data, or publishing variations of the same data with greater or lesser reliability. Identifying which is the authoritative data for particular purposes, and which is potentially less reliable, may be important.

6.3.1.3 Unstructured documents

SAKI tries to use information in unstructured documents intended for human consumption, such as MS Office (Word, PowerPoint, Excel) and PDF documents, web pages, etc. Parsing errors similar to those discussed for MTF messages can occur, but in this case the parsing process is particularly brittle and it is important to be able to flag when expected information may be missing because of these errors. The ability to show the source document is also important in this case.

Unstructured documents are generally not a real-time resource, so the age of the information contained within it is an important consideration, and the ability to represent this in some way may be an important consideration to avoid undue emphasis on out-of-date information.

6.3.1.4 Structured documents

Information can also be sourced from structured documents, typically in XML or JSON formats, which are often generated by a computer program or from databases containing manually entered inputs. As such, structured documents can introduce uncertainty through:

- Data entry errors giving rise to inconsistent data, which can (sometimes) be identified due to inconsistency with the document schema, and in this case it may be important to represent this inconsistency.
- Incomplete metadata associated with the document. Depending on the nature of the metadata, it may be important to flag that it is incomplete. This can also give rise to errors in the data transformation stage, even if the data itself is good.
- Inconsistent or ambiguous schema/ontologies between documents, which may give rise to errors during the data transformation stage that may need to be represented or otherwise flagged.
- Out-of-date information, so it may be important to represent the currency of the information in some way. This may be particularly important in the case where the document represents a 'snapshot' of a database.

6.3.1.5 Databases

The information contained within databases can be obtained from a variety of sources:

- Manually entered by a human operator
- Automatically recorded from a sensor or otherwise automated data feeds (e.g. track data)
- Automatically recorded from automated data processing
- Extracted from unstructured documents, including from 'open-sources'; and
- Extracted from structured documents.

As such, many of the issues associated with the data sources discussed above may also apply to the information contained within databases:

- Data entry errors
- Incomplete metadata associated with data
- Inconsistent or ambiguous schema/ontologies between databases
- Out-of-date information
- Conflicting data in different databases, requiring an 'authoritative' source to be identified and represented in some way
- Representing and indicating corrections made to database data
- Representation of synthetic vs real data stored in databases
- 'Noisy' data due to the accumulation of various errors in 'big-data' sets. This is particularly relevant when parsing errors can introduce errors in the information extracted from unstructured text. In this case, the reliability of the data needs to be represented in some way.

6.3.2 Transformation

In SAKI, the primary goal is to extract the appropriate information from the available data sources and integrate it to provide the information products relevant to the JOC in a relevant manner. This requires data curation, which involves:

- Identifying the relevant data sources. This is not necessarily a 'one-off' process, as linked data within one data source, particularly when dealing with open-source data, could specify supplementary data sources required to interpret the original data.
- Verifying that the data does include the required information (for example, parsing errors during the acquisition stage could mean that some data is missing)
- Cleaning the data to remove invalid subsets
- Transforming the data into the required formats
- Integrating it with other data sources of interest. This includes: associating it with other data related to an 'event' of interest; handling conflicting data; removing duplicates; and fusing the data to provide the required information products.

Identifying, verifying, cleaning and transforming data are the processes that identify and realise some of the errors associated with the original data sources, and allow an evaluation of the uncertainty/reliability of the information. The integration process treats some of this uncertainty (for example by exploiting the authoritative source in cases of conflicting data), and evaluates how this uncertainty affects the final information products.

The information products from the transformation stage can be varied, and include, for example, information about an incident, military unit, defence capability, defence establishment, civilian infrastructure, or a weather, geological, or fire event. The transformation stage can introduce its own errors and uncertainties into these products:

- Association of information used to provide an information product may be incorrect, particularly when dealing with unstructured sources, inconsistent schema/ontologies for structured data, or apparent duplicates. In this case, it may be important to provide some representation of the possible alternative associations.
- Incomplete information required to provide an information product may lead to uncertainties associated with that product. This is independent of the reliability of any individual data source used to make up that product. The impact on the uncertainty associated with the product is highly dependent on the nature of the product, but it may be important to represent this incompleteness in some way.
- Aggregation of classified information can, in principle, raise the classification of the aggregated information above that of its parts. In this case, the information products may be downgraded (by removal of information) to a classification appropriate for the operating environment. It may thus be important to provide some representation that this has occurred and that higher classification data may potentially be available on another system.

6.3.3 Visualisation

SAKI is designed to allow a user to search for and/or select relevant information, and display aggregated information about the results found. It is often important for the user to be able to validate the information found, and manually extract related information. As such, it needs to display:

- Source documents, messages, etc.
- Lists and summaries of search results
- Tracks and geospatial features
- Aggregated multimedia information related to an event, military unit, defence capability, defence establishment, or civilian infrastructure.
- Geospatial context, coordinates, areas of effect and time evolution of same.

The visualisation artefacts/ambiguities/issues that can be introduced with these displays are:

- How can you visualise content that didn't parse and so isn't searchable, but may still be relevant to the query?
- Search results are often 'paged' when a large number of results are returned. Results beyond the first page may never be reviewed, making the sorting algorithms crucial.
- Dynamic updates to search results can cause spontaneous re-ordering of results, confusing the user.
- When search results are linked to a geospatial display, depending on the sorting criteria this can give a misleading impression of the geospatial distribution of results overall.
- A geospatial display may be presented at an inappropriate scale, excluding or hiding geospatial context.
- A geospatial display may be too cluttered for a user to extract useful information from it.
- Geospatial clustering of geospatially adjacent features is a common approach to reducing clutter in a geospatial display at different scales. Clustering algorithms can potentially cluster content in a non-intuitive way (e.g. it may cluster purely on spatial separation and not on feature).
- Overlapping map layers may interfere with each other, producing a shading or colourisation effect that looks nothing like the source layers, hence risking incorrect interpretation. Similarly, overlapping layers may mask important features.
- Overlapping or adjacent map symbols may actually form shapes that can be mistaken for other symbols.

6.4 Uncertainty visualisation for JOC

SAKI deals with large amounts of information that comes from many sources in a variety of formats, ranging from sensor data to unstructured documents. One big challenge in the development of SAKI is how to effectively fuse and display numerous instances of uncertain and noisy information for better situation awareness and decision making. The commander must make decisions under time pressure, but ignoring the fact of information uncertainty could lead to severe consequences in the military domain. SAKI exposes many issues relevant to dealing with uncertainty in JOC, which include:

- It is necessary to develop visualisation methods in SAKI for depicting multiple kinds of uncertainty. As shown in Table 1 (Page 3), uncertainty can be classified into three types as spatial, temporal and attributes of data. However, these categories are often interdependent, and the category boundaries are hard to delineate (MacEachren et al., 2005). This raises the issue of how to visualise compounded uncertainty information. For example, geo-references for a particular bushfire event (see Figure 28) could include three types of uncertainties: spatial uncertainty in its position due to fuzzy descriptors; temporal uncertainty due to low reporting rates; and attribute uncertainty in its status due to unreliable or conflicting reports. In this case, different visualisation techniques could be applied to represent each aspect of uncertainty. As discussed in Sections 3 and 4, temporal uncertainty could be represented by opacity, and spatial uncertainty could be represented by blurring. Uncertainty in its status (e.g. Out of Control/Contained) could be depicted by using degraded icons. However the effectiveness of this potential approach should be verified by empirical studies to see whether the operator maintains situational awareness of the different uncertainties in data.

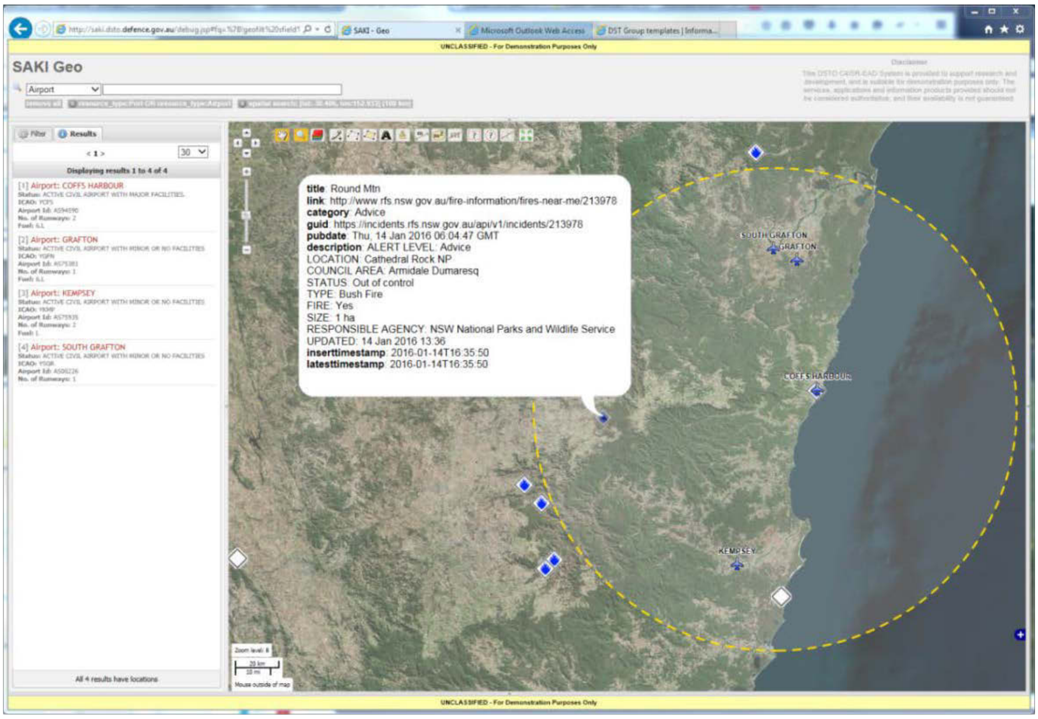


Figure 28: Screenshot of SAKI's geospatial visualisation system

- Most work cited in this report has focused on numerical uncertainties such as temporal and spatial error, with only limited attention given to more abstract forms of uncertainty such as consistency and credibility. As discussed in the preceding sections, SAKI also has to represent these more abstract concepts. For these cases it may (or may not) be sufficient to provide a visual indication to the user that such uncertainty exists through highlighting and/or colour mapping.

- A related issue is how to represent uncertainty in those cases where the SAKI system has been unable to interpret, for various reasons, the information available to it. In some cases SAKI may need to advise the user that such information exists, represent the nature of the incompleteness and provide an appropriate visualisation. For example, badly formatted geospatial coordinates would mean that there is no geospatial representation of the information on the SAKI geo display. This could potentially be represented using an interactive notification which provides elaboration on the information that is available, and what the problem with it is, when the user's mouse hovers over or clicks it.

- The literature has shown that experts and novices cope differently with less reliable information in decision making, and may require different visualisations (Kobus et al., 2001, John et al., 2000, Omodei et al., 2005). It is unlikely that all users of SAKI are subject matter experts in all of the different data sets, and further, in every task they are required to do. The users' level of experience needs to be considered in the selection of uncertainty visualisation approaches and interface design, perhaps by incorporating user models that tailor the display to suit their level of experience and role.

- User preferences for the representation of uncertainty have been shown to be correlated with the performance of decision making (Gerharz and Pebesma, 2009). It is important to provide a user interface which allows users to intuitively access and modify the uncertainty representation approach used, according to operational roles or situation changes:
    - The user interface should allow management of individual overlays, cropping of unnecessary data sets and, adjustment of the interface design or visualisation parameters to focus on important uncertainty features
    - It would be desirable to provide multiple ways of displaying uncertainty attributes to support different user preferences and manage cognitive loads for different roles and tasks. However, as discussed in §4.2.2, users may not always prefer the most effective representation, so some constraints would need to be applied to user configuration, perhaps based on user and task models.
    - Similarly, users may not be the best judge of their situation awareness requirements and when they have enabled display of too much information (Omodei et al., 2005). It may be useful to incorporate into the display one or more of:
        - metrics that allow the user to monitor their own performance

  - automated monitors that alert them when they may have added too much to the display
  - constraints that restrict how many dimensions of the data they can display at any given time.

- An avatar could be used to provide high-level narratives of a situation and convey different levels of reliability or uncertainty to users. This may also be appropriate, for example, when summarising the status of an evolving event. Other visualisation modalities may also be appropriate for conferring different levels of confidence in uncertain information.

- Multimodal interfaces could be incorporated in SAKI to display a large amount of data by reducing the dimensionality of the data that needs to be presented visually. In particular, multimodal channels could enhance the users' ability to process information simultaneously and direct attention to critical information. For example, an audible alarm could alert users when a bushfire changes status to 'Out of Control', or aural channels could be used to represent otherwise overlapping visual layers (such as weather and fire-affected regions) which could cause interference between shading and colouring effects.

- An evaluation framework is needed to investigate the impact of visualisation approaches in general, and uncertainty visualisation in particular, on the users' situational awareness. For the JOC case, factors that need to be taken into account include:
  - Numerous and repetitive user tests may be required to iteratively evaluate and refine a visualisation approach, because of the lack of relevant empirical studies or comprehensive guidelines.
  - It is crucial to recruit participants who are experienced with the tasks undertaken, and who can provide feedback on practical and effective system designs. This also might be useful to study the effect of experience on decision making with uncertainty. The pool of experienced users for the JOC case is limited, and they will have limited time available to participate in system evaluation.
  - Further to this, the information requirements for the JOC case are diverse and highly dynamic, so opportunities to gain experience with a particular role (and its information requirements) are limited. However, this also means that the inclusion of uncertainty visualisation may provide significant improvements to the user's decision making performance.
  - Better understanding is needed of the cognitive processes for interpreting information with uncertainty so that effective mechanisms can be applied to meet the diverse and dynamic requirements for JOC.

- Reducing the sources of uncertainty for SAKI could mitigate the requirement to represent them. Approaches to this could include:

- Development and/or application of more advanced parsing algorithms using recent advances in machine learning, for a larger variety of documents, to deal with ambiguities in language and interpretation of context.
- Establishment and wider community uptake of consistent standards for schema/ontologies to avoid inconsistent or incorrect interpretation of information sources, and to support meaningful association of information, including standardisation of geospatial formats (e.g. polygon representations). The wider community awareness of 'big data' and data science approaches shows promise in this regard.

7. Conclusion

Military commanders are typically required to make critical decisions and develop plans, using large and complex collections of data, in a limited time frame. They must do this without precise knowledge about the operating environment or the intent, capabilities or location of the adversary. It is important that commanders understand the associated uncertainties so that they can understand and mitigate the operational risks involved in this inherently risky enterprise. Therefore it is important for decision support tools to make users aware of the uncertainties in the information being displayed in an appropriate and timely manner, while avoiding information overload. However, most visualisation techniques have been designed around the assumption that the data being visualised is free from uncertainty.

This report introduced the main conceptualisations and approaches for representing uncertainty suggested in the literature. There are eleven categories of uncertainty that have been identified in the literature that relate to different information requirements. These uncertainties can be introduced during the data acquisition, data transformation, or data visualisation processes. How uncertainty needs to be represented depends on the nature and source of the uncertainty, and a number of visualisation techniques have been presented. However, there is an enduring need to ground these techniques in perceptual and cognitive theory, and more systematic empirical studies into the effectiveness of these techniques are needed before results can be generalised to other application contexts.

Empirical studies carried out on the effect of uncertainty on decision making have found marked differences in performance between experienced and inexperienced users. The decision times for experienced users were not affected by uncertainty, while the decision times for inexperienced users were significantly longer. Interestingly, visualisation of uncertainty has been found to improve decision making performance for relatively easy tasks, but not when dealing with more difficult tasks. Perhaps in these cases other considerations dominate. Studies have also shown that user experience is particularly important in the selection of participants for empirical studies into uncertainty representation techniques. Clearly, the skills and experience of participants in these empirical studies need to be representative of the skills and experience of the target user group, which could be problematic for applications targeted at operational commanders, who have a unique skill set.

Several empirical studies have also looked at the effectiveness of different uncertainty visualisation approaches on decision making in different contexts. Dynamic uncertainty representation techniques (e.g. animation) were generally found to be less effective than static techniques (e.g. glyphs) in decision making tasks. Somewhat surprisingly, the addition of textual annotations of confidence to a glyph was found to give poorer performance than the glyph alone some tasks, perhaps indicating the presence of information overload. In other studies, different uncertainty representations were found to suit different user requirements in the same application, suggesting that some degree of tailoring may be required to meet multiple user roles. This should be treated with caution however, as other studies have also shown that user satisfaction with information products does not necessarily coincide with improved situational awareness in general, and so user preferences for different uncertainty representation techniques do not necessarily coincide with best decision making performance. System metrics and governance frameworks may be needed to help manage this complexity.

Other approaches to uncertainty visualisation could use the method of representation itself to attribute confidence in the information presented. For example, users have greater confidence in information when it is presented textually than when it is presented by a virtual human. Thus, information with low uncertainty could be presented to the user as text, while information with high uncertainty could be presented to the user by an avatar. Further studies could also explore how users attribute confidence to information presented using other visualisation modalities.

General guidelines for visualisation can be applied to help formulate an uncertainty visualisation approach suitable for a particular context, once the relevant components of uncertainty, their relationships to the data, and the desired decision making outcomes are understood. However, there are limited guidelines available for representing multiple types of uncertainty in decision making applications in particular. More study is needed in how to depict multiple forms of uncertainty in the same display, and how providing multiple types of uncertainties affects the users' understanding of the information. User centred design, iterative approaches to development, and methods for assessing relevant performance metrics, are considered crucial given the sensitivity of decision making outcomes to context, user experience, and user roles.

Some of these considerations have been discussed in the context of the situational awareness for the Joint Operations Command, although empirical studies and further conceptual refinement are needed to target their particular user requirements. Significant barriers to uncertainty visualisation research in this context are the availability of experienced users for empirical evaluation, and the dynamic nature of their visualisation requirements across a broad range of information types. The dynamic nature of their requirements means that many of these users may be relatively inexperienced with a particular task or display, which may make it easier to find experiment participants representative of this target group. It also indicates that visualisation of the associated uncertainties may provide significant benefits to decision making performance in this context.

Finally, how decision making with uncertainty translates to operational risk is an area that requires further study. In the studies presented in the literature the performance of the decision maker was evaluated using metrics such as response time and the user's confidence in the outcome. Whether the representation of uncertainty translates to a better appreciation of operational risk, and more effective mitigation strategies, has not been considered in this work. Studies that model and evaluate operational risk could help address this question.

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19. ABSTRACT

Uncertainty is inherent in all real world settings and it creates ambiguities that make decision making complex and difficult. For decades, uncertainty visualisation has been a prominent topic in the research of military decision making. Even if data is free from uncertainty, errors can occur in the process of turning the data into the 'picture'. Ignoring the fact of information uncertainty could lead to severe consequences in the military domain. This report presents an overview of the theoretical concepts and definitions of uncertainty, and the uncertainty visualisation techniques that have been investigated to date. It discusses the literature on the impact of uncertainty visualisation on decision making, and introduces recommended guidelines and systematic strategies for uncertainty visualisation. Finally, it discusses how this work can be applied to support situation awareness and decision making in the Australian Defence Force's Joint Operations Command.