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A Strategy for Uncertainty Visualization Design

Anna-Liesa S. Lapinski

Defence R&D Canada – Atlantic

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Abstract

Visualizing uncertainty can be a challenging endeavour. In an attempt to minimize the challenges, this paper defines a systematic approach to designing a visual representation of uncertainty called the Uncertainty Visualization Development Strategy (UVDS). The strategy helps in the understanding of both the data and the uncertainty. The UVDS has eleven steps which include: identify the uncertainty visualization task; understanding the data that need to have their uncertainty visualized; understanding why uncertainty needs to be visualized and how the uncertainty visualization needs to help the user; deciding on the uncertainty to be visualized; deciding on a definition of uncertainty; determining the specific causes of the uncertainty; determining the causal categories of the uncertainty; determining the visualization requirements; calculating, assigning, or extracting the uncertainty; trying different uncertainty visualization techniques; and obtaining audience opinions and criticisms. The UVDS has been created specifically to help the designer produce comprehensive uncertainty visualizations, allow the designer more time to focus on the creative aspects of the work, and give those trying to understand what is behind the design a clearer understanding. As an example application of the UVDS, it is applied to current research regarding uncertainty visualization for the Canadian Recognized Maritime Picture (RMP).

Résumé

Visualiser l'incertitude peut être une entreprise extrêmement difficile. Afin de minimiser les difficultés, le document ci-joint propose une approche systématique pour la conception d'une représentation visuelle de l'incertitude : la Stratégie de visualisation de l'incertitude (SVI). Cette stratégie aide à comprendre les données et l'incertitude qui s'y rattache. La SVI comporte 11 étapes : définir la tâche de visualisation de l'incertitude; comprendre les données dont l'incertitude doit être visualisée; comprendre pourquoi l'incertitude doit être visualisée et comment cette visualisation aidera l'utilisateur; décider de l'incertitude à visualiser; donner une définition de l'incertitude; déterminer les causes précises de l'incertitude; déterminer les catégories causales de l'incertitude; déterminer les besoins en matière de visualisation; calculer, attribuer ou extraire l'incertitude; essayer différentes techniques de visualisation de l'incertitude; et recueillir des opinions et des commentaires critiques. La SVI a été créée spécifiquement pour aider le concepteur à produire une visualisation complète de l'incertitude, pour permettre au concepteur de consacrer plus de temps aux aspects créatifs du travail, et pour aider les intéressés à mieux comprendre le système de visualisation. Exemple d'application : la SVI est utilisée dans les recherches en cours sur la visualisation de l'incertitude pour le Tableau de la situation maritime (TSM) du Canada.

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Executive summary

A Strategy for Uncertainty Visualization Design

Anna-Liesa S. Lapinski; DRDC Atlantic TM 2009-151; Defence R&D Canada – Atlantic; October 2009.

Introduction: Achieving effects-based visualization and awareness for the decision maker is an important area of modern defence research. Making effects-based decisions in the defence environment often involves relying on information from many sources such as sensors and human intelligence. In order to make an educated decision (effects-based or otherwise), it is important to understand the uncertainty in the information being used to make that decision; however, the visual representation of uncertainty is often overlooked in visualizations. A decision maker cannot form a clear awareness of the situation without understanding the inherent uncertainty in the information that is being visualized.

While it is a well defined research area within the topic of information visualization, uncertainty visualization is lacking proven (human factors) theory, particularly in the defence domain, to help those who need to develop uncertainty visualizations. In an attempt to minimize the challenges encountered in uncertainty visualization, this paper defines a systematic approach to designing a visual representation of uncertainty called the Uncertainty Visualization Development Strategy (UVDS). The strategy helps in the understanding of both the data and the uncertainty.

Results: The UVDS that is presented has eleven steps which include: identify the uncertainty visualization task; understanding the data that need to have their uncertainty visualized; understanding why uncertainty needs to be visualized and how the uncertainty visualization needs to help the user; deciding on the uncertainty to be visualized; deciding on a definition of uncertainty; determining the specific causes of the uncertainty; determining the causal categories of the uncertainty; determining the visualization requirements; calculating, assigning, or extracting the uncertainty; trying different uncertainty visualization techniques; and obtaining audience opinions and criticisms. The UVDS can help the visualization designer produce comprehensive uncertainty visualizations, allow the designers more time to focus on the creative aspects of the work, and give those trying to understand what is behind the design a clearer understanding. As an example application of the UVDS, it is applied to current research regarding uncertainty visualization for the Canadian Recognized Maritime Picture (RMP).

Significance: Decision making quality is improved from understanding the uncertainty in the data and information being used in the decision process. For example, an RMP with none of the uncertainty in its contacts displayed looks like all the information is current, all the ships are currently in the positions displayed on the map, all the information comes from sources that never have mistakes, and the entire area is monitored by sensors feeding the RMP. For an informed decision to be made regarding the RMP, whether it is regarding where to send a surveillance asset, how to prioritize the order a group of ships should be investigated, etc., more information on the uncertainty surrounding the contacts in the RMP needs to be known. While the uncertainty levels can be determined by investigating each contact one by one, that is a time consuming process if there are more than a few ships to be investigated. Having a visual representation of the uncertainty overlaid onto the RMP can help a decision maker quickly assess a situation and, if

necessary, decide on which contacts or areas are worth a closer look before a decision is made. This simple development strategy for creating uncertainty visualizations can be applied to any situation (not just defence related) where uncertainty needs to be visualized.

Future plans: This is the first of a series of Technical Memorandums (TMs) aimed at creating foundational documents on the topic of uncertainty visualization which can be used in defence applications. In addition, the aim of these TMs will be to push forward the research of uncertainty visualization, particularly in the defence field.

Sommaire

A Strategy for Uncertainty Visualization Design

Anna-Liesa S. Lapinski; DRDC Atlantic TM 2009-151; R & D pour la défense Canada – Atlantique; Octobre 2009.

Introduction : Fournir aux décideurs des outils de visualisation et de connaissance de la situation est un secteur important de la recherche pour la défense. Pour prendre des décisions basées sur les effets, les spécialistes de la défense doivent souvent se fier à des informations provenant de nombreuses sources, comme les capteurs et l’intelligence humaine. Pour prendre une décision éclairée (basée sur les effets ou autre), il est important de connaître le degré d’incertitude des informations utilisées dans la prise de décision. Cependant, la représentation visuelle de l’incertitude est souvent négligée par les systèmes de visualisation. Un décideur ne peut pas avoir une vision claire de la situation sans connaître le degré d’incertitude des informations visualisées.

Bien qu’il s’agisse d’un champ de recherche bien défini lié à la visualisation de l’information, la visualisation de l’incertitude souffre de l’absence d’une théorie éprouvée (facteurs humains), surtout dans le domaine de la défense. Afin de minimiser les difficultés liées à la visualisation de l’incertitude, le document ci-joint propose une approche systématique pour la conception d’une représentation visuelle de l’incertitude : la Stratégie de visualisation de l’incertitude (SVI). Cette stratégie aide à comprendre les données et l’incertitude qui s’y rattache.

Résultats : La SVI comporte 11 étapes : définir la tâche de visualisation de l’incertitude; comprendre les données dont l’incertitude doit être visualisée; comprendre pourquoi l’incertitude doit être visualisée et comment cette visualisation aidera l’utilisateur; décider de l’incertitude à visualiser; donner une définition de l’incertitude; déterminer les causes précises de l’incertitude; déterminer les catégories causales de l’incertitude; déterminer les besoins en matière de visualisation; calculer, attribuer ou extraire l’incertitude; essayer différentes techniques de visualisation de l’incertitude; et recueillir des opinions et des commentaires critiques. La SVI peut aider le concepteur à produire une visualisation complète de l’incertitude, permettre au concepteur de consacrer plus de temps aux aspects créatifs du travail, et aider les intéressés à mieux comprendre le système de visualisation. Exemple d’application : la SVI est utilisée dans les recherches en cours sur la visualisation de l’incertitude pour le Tableau de la situation maritime (TSM) du Canada.

Portée : Pour améliorer la prise de décision, il faut connaître le degré d’incertitude des données et des informations utilisées dans le processus de prise de décision. Par exemple, dans un TSM, s’il n’y avait aucune indication sur l’incertitude associée aux contacts, on pourrait croire que toutes les données affichées sont à jour, que tous les navires sont actuellement à l’emplacement indiqué, que toutes les informations proviennent de sources qui ne font jamais d’erreurs, et que l’ensemble du secteur est couvert par des capteurs qui « nourrissent » le TSM. Pour prendre des décisions éclairées à l’égard du TSM (ex. : déterminer où sera installé un équipement de surveillance, établir l’ordre dans lequel les navires seront examinés, etc.), il faut avoir plus d’informations sur l’incertitude associée aux contacts. Le niveau d’incertitude peut être déterminé en examinant tous les contacts un à un, mais c’est un processus qui prend trop de temps s’il y a plus que quelques navires à examiner. Lorsqu’une représentation visuelle de l’incertitude est ajoutée au TSM, le

décideur peut évaluer rapidement la situation, et décider si nécessaire des contacts ou des secteurs qui méritent d'être examinés plus attentivement avant qu'une décision soit prise. Cette stratégie toute simple de visualisation de l'incertitude peut être appliquée à toutes les situations (pas seulement dans le domaine de la défense) où l'incertitude doit être visualisée.

Recherches futures : Ceci est le premier d'une série de mémoires techniques (MT) conçus comme des documents de base sur la visualisation de l'incertitude, et destinés aux applications de la défense. Ces MT ont aussi pour objectif de faire progresser la recherche sur la visualisation de l'incertitude, surtout dans le domaine de la défense.

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1 Introduction

Visualizing uncertainty is a challenging endeavour. Perhaps this is because uncertainty is always calculated or recorded with respect to other primary data. In a sense, uncertainty is more like metadata to primary data. Thus, the act of visualizing the uncertainty has to be supported by an understanding of both the uncertainty itself and the primary data. The primary data and how these data are currently being used act as two constraints on the visualization solution. It is challenging to develop innovative methods to visualize uncertainty given these innate constraints; however, many have begun to foray into this research area [1-12].

As of yet, proven theory for visualizing uncertainty is lacking in the literature. Some guidance can be found in the general visualization theory of Tufte [13], Bertin [14], Ware [15], and Chambers *et al.* [16]. Their theories have been applied in the literature to assess uncertainty visualizations [17, 18] as well as to guide designs [5]. As much of uncertainty visualization requires the presentation of multidimensional data, Cluff's [19] critiques which draw on Bertin [14] and Chambers *et al.* [16] are also worth noting. Some guidance can also be found by surveying the literature for trends. One trend, for example, is that the most popular technique for visualizing uncertainty is to integrate the uncertainty data into a visualization of the primary data or spatial coordinates of the primary data (e.g., [4-8]). With the absence of solid, experimentally proven, uncertainty visualization theory, the uncertainty visualization designer is left to use educated guesses augmented by their own creativity, to create their uncertainty visualization.

This paper attempts to make visualizing uncertainty somewhat less challenging by outlining a systematic approach, called the Uncertainty Visualization Development Strategy (UVDS), for designing an uncertainty visualization. The UVDS is an eleven step strategy for visualizing uncertainty. Each step is explained and described in this paper. The goal of the UVDS is to guide the visualization designer such that the uncertainty visualization that is developed suits the primary data, the uncertainty being visualized and the visualization user's needs.

The objective of this paper is to document a step by step practical method for creating uncertainty visualizations. The user of the UVDS will still be required to make educated guesses, be creative and be aware of the primary data, but by following this systematic approach, many of the easily forgotten but important details will be systematically accomplished. The strategy should leave the user more time to focus on the creative aspect of the visualization. In addition, when documenting work on a new visualization, reporting on each step in the development strategy should help the audience better understand the work. For those who are already trying to visualize a particular uncertainty, implementing the UVDS will help clarify the underlying goals of the effort and identify omitted steps that might be hampering progress.

This strategy can be used in conjunction with previously developed visualization theory, postulates or frameworks that aim to guide creative or functional aspects when creating an optimal visualization. The UVDS does not tell the user how to create a visualization, how to optimize the human-visualization interaction, or what the user and visualization requirements are, but rather it provides the user with an opportunity to address such things. The UVDS is a foundation onto which existing visualization work can be applied. Such work could include the previously mentioned Tufte [13], Bertin [14], Ware [15], and Chambers *et al.* [16], as well as Amar and Stasko [20], Zuk and Carpendale [21], and Kreuseler *et al.* [22], to name a few. There will likely be occasion, such as in the framework developed by Amar and Stasko [20] to bridge analytic gaps in visualization design, when tasks in the strategy overlap (and therefore complement) design frameworks.

This paper presents a simple development strategy for developing uncertainty visualizations. In the following section, the steps of the UVDS are discussed and defended. In Section 3, ongoing work regarding uncertainty visualizations for the (Canadian) Recognized Maritime Picture (RMP) is used to illustrate the completeness of the UVDS. Final remarks are made in the remaining section.

2 Uncertainty Visualization Development Strategy (UVDS)

The UVDS represents a series of steps, recipe, or process to be applied when an uncertainty visualization needs to be designed. Such recipes are important for multi-step processes, because they help guide the designer and ensure steps of the process are not forgotten. The UVDS is illustrated in Figure 1. The first step requires the designer to *identify the uncertainty visualization task*. This needs to be accomplished in only vague terms as much of the strategy will help illuminate the intricacies of the problem. For example, stating “the uncertainty of [such-and-such] data needs to be visualized for [so-and-so, *or* such-and-such website, *or* such-and-such application, etc.],” could be sufficient to accomplish this step. This is an obvious first step but is included to act as a guiding statement for the remaining work.

The second step is also quite straightforward and would hopefully always be done automatically. However, the degree to which the step is completed is also critical. *To understand the data that need to have their uncertainty visualized* ensures that the person designing the visualization understands the primary data to which the uncertainty is related. It is useful, for example, to know the origin of the data; to understand the units associated with the data; to understand the precision of numerical values; to understand the precision to which something is being visually rendered or reconstructed; to know if the data being visualized have been modified (e.g., averaged); to know if the data are continuously being generated or if the data set is static; to know the data format and limitations introduced by the format; etc. Perhaps more difficult but equally important, the user should understand any intricate relationships that exist within the data (e.g., how changes in one type of data influence other data). This step in the strategy can make the subsequent steps easier and may illuminate some constraints on the uncertainty visualization.

To *understand why uncertainty needs to be visualized* is essential to creating an effective uncertainty visualization. In some cases, this understanding will highlight the fact that the same data should be visualized differently for different audiences. For example, a designer representing positional uncertainty of in-flight airplanes for an air traffic control officer will take a different approach to uncertainty visualization as compared to presenting the same data to a group of scientists who are studying plane traffic patterns and the related uncertainties. In these cases, the requirements for the visualizations are different; one case is dominated by safety while the other dominated by a statistical representation of the observations. In this step the designer must therefore comprehend *how the uncertainty visualization needs to help the user* (even if they, themselves, are the user).

The next part of the strategy has four steps which have been grouped together in Figure 1 to indicate that the steps are interconnected and may be completed in any order. For one step in the group, the designer has to *decide on the uncertainty to be visualized*. This is important because there may be multiple uncertainties associated with the data. For this step the designer needs to recognize the uncertainties that could be visualized and then narrow these down to the uncertainties that should be visualized. Selecting the proper uncertainty to be visualized is critical to meeting user requirements. This step is not placed earlier in the strategy because the earlier steps may result in showing that the preconceptions the designer had at the beginning of the

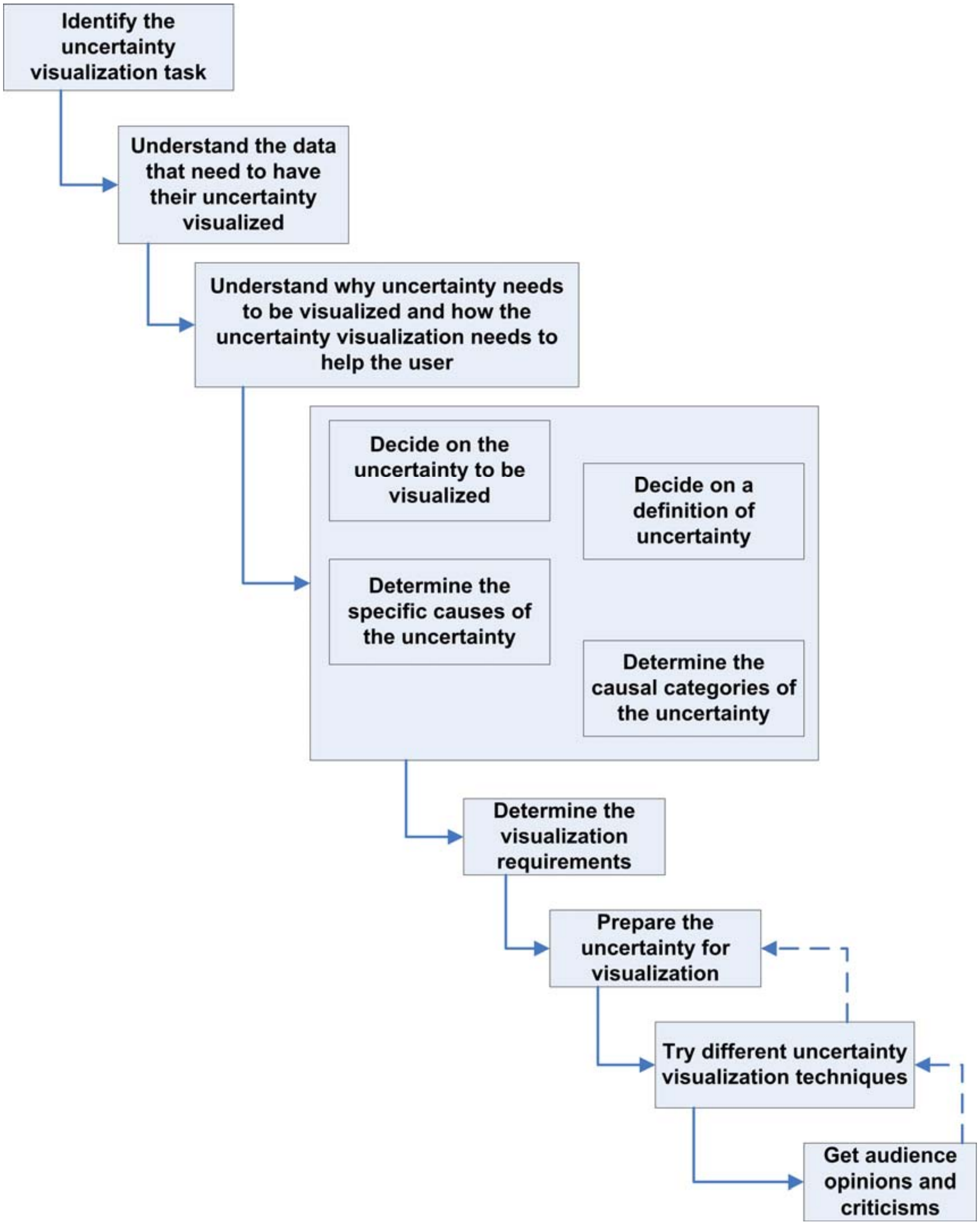

Figure 1: A graphical ("waterfall") representation of the UVDS.

UVDS concerning what uncertainty needed to be visualized were not fully understood at that time.

An essential step within this group is for the designer to *decide on a definition of uncertainty*. The definition, once formalized, may indicate that the original preconception of the uncertainty to be visualized is too broad (or restricting) and, therefore, either the definition, the uncertainty to be visualized, or both will need to be revised. In addition, in the uncertainty visualization literature it is common for authors to comment or show that there are many definitions of uncertainty [7, 10-12, 18]. The existence of multiple definitions can create misunderstanding among designers and users. The designer cannot and should not assume everyone is working from the same definition of uncertainty. Again, this step is not placed earlier in the strategy because the increased understanding of the problem that the second and third step of this strategy brings to the designer will feed into defining what is meant by uncertainty. The designer may feel more comfortable doing this step before they decide on the uncertainty to be visualized which is, as mentioned earlier, why this area of Figure 1 is non-linear.

The designer should also *determine the specific causes of the uncertainty*. For example, consider the position of a ship received every 30 minutes. Between position fixes, one cause of uncertainty in knowing the ship position is the time lag between position reports. Note that this has nothing to do with positional accuracy or precision, but rather is related to the time-late nature of the data delivery to the user. Isolating the actual cause of the uncertainty can illuminate the need to group or ungroup particular uncertainties when visualizing. This step (and also the next step) helps to ensure that an uncertainty that needs to be included in the visualization is not being overlooked. Determining the specific causes of uncertainty can often illuminate important uncertainties not previously recognized or additional components of the uncertainty of interest. These may need to be incorporated into the calculations or visualization. For example, in the previous ship example, there is also uncertainty associated with the positional data itself (i.e., the precision and accuracy of the positional data). Realizing the multiple-component nature of the uncertainty may require a revisit to the two steps described previously.

It is also useful to *determine the causal categories of the uncertainty*, or in other words the categories the specific causes fall into. Table 1 lists the causal categories, developed from related lists by Plewe [23] and Griethe and Schumann [10]. The most important reason to determine the causal categories is to illuminate what types of uncertainty the designer is dealing with. This information will be valuable when deciding how to visualize the uncertainty; e.g., uncertainty due to data age may need to be represented differently than uncertainty due to known data corruption. In addition, sometimes it can be easier to think of the broad causal categories before narrowing down the specific causes in the previous step. Again, completing this step may require the designer to revisit the previous steps in this grouping illustrated in Figure 1, perhaps because they realize their definition is too narrow or the identified uncertainty to be visualized is incomplete.

At this point in the design strategy, the focus shifts to the visualization itself. To *determine the visualization requirements* the designer, from a visualization point of view, identifies the needs of the visualization. For example, if the uncertainty is being visualized concurrently with the primary data, is there a requirement for the uncertainty visualization to be the dominant feature? Another question of requirement would be at what level of detail the audience should comprehend the uncertainty: e.g., the audience simply knows that there is uncertainty; the

Table 1: Causal Categories of Uncertainty.

Causal Categories of Uncertainty	**Definition**
Data Acquisition Limitation	The limitation caused by the accuracy and precision of the data acquisition device, including the human senses and mind.
Data Acquisition Error	An error in a datum acquisition that occurs at the time of acquisition. The error can be accidental or deliberate. The resulting datum can be erroneous or completely absent.
Phenomenon Discretization	The discretization, at the point of datum acquisition, of a phenomena or its attribute that is in reality continuous in space, time or another similar dimension. In other words, the act of acquiring data at intervals for something that is continuous. (Note: Discretization (or sampling) of data <u>after</u> data acquisition would fall under Transformation.)
Noise	Extraneous background activity that produces unwanted influence on the acquired data.
Ambiguous Data	Data that cannot be interpreted correctly without further information. The ambiguity could be due to a lack of reference or simply confusion as to how to interpret the data.
Subjectivity	Subjective influence in the data.
Data Age	The age of the data from the moment of acquisition. This is a cause of uncertainty only in cases where the data are time dependent.
Data Corruption	Corruption of data at some point during the transfer-storage-manipulation-usage process due to human or machine error. This can occur anytime after the moment of data acquisition for the entire lifecycle of the data.
Data Extrapolation & Interpolation	Extrapolating or interpolating data from indirect evidence. The extrapolated or interpolated data has an inherent uncertainty.
Transformation	The changing of data from their original form or format.
Misinterpretation	A mistake made in interpreting the data.

audience can distinguish between relative degrees of uncertainty; the audience can extract values of uncertainty; etc.

To *prepare the uncertainty for visualization* is to do what is necessary to have the required uncertainty ready to be used in the visualization. This could involve calculating uncertainty from collected data, transforming uncertainty measurements into the proper units, assigning uncertainty, extracting uncertainty from collected data, etc. The past steps may have also illuminated that the uncertainty data need to be prepared in ways that were not evident at the outset. Including this step at this point in the strategy allows for this new understanding to be taken into consideration when preparing the data. For example, using the previous ship example, the multiple uncertainties may need to be properly combined.

To *try different uncertainty visualization techniques* is the creative part of this strategy. It is the step where the designer takes what they have learnt from the strategy and applies their own creative ideas, visualization theory, past experience, or techniques they have seen elsewhere, to create ways of visualizing the uncertainty. It may become obvious in this step that the uncertainty data have to be manipulated further, thus the previous step may need to be revisited.

To *get audience opinions and criticisms* includes doing user studies, usability studies, etc. This step is arguably the most important step of the strategy because it applies the visualization to a user-focused application. In addition, the results of structured user and usability studies can guide future work. This step will likely require a revisit to the previous step once results are obtained.

It is important to note that these last two steps are essentially the “trial and error” method. One goal of this strategy is to minimize the trial and error iterations. In turn, this will minimize designer and user frustrations while optimizing product delivery time.

3 UVDS Illustrated Through a Canadian Recognized Maritime Picture Uncertainty Visualization Experiment

In the previous section, the Uncertainty Visualization Development Strategy was described. The UVDS is now mapped to uncertainty visualization work that has been done with regards to the Recognized Maritime Picture (RMP) created and maintained by the Canadian military's Regional Joint Operations Centres (RJOCs). The UVDS was developed prior to this RMP uncertainty visualization research but not actively applied during the research. Nonetheless, the UVDS can be easily mapped to the work done in the project. Further information on the details and results of this visualization research can be found in Matthews *et al.* [24] and Matthews and Rehak [25].

The RMP is a tool used to develop Maritime Domain Awareness (MDA) for Canadian military operation centres. In its common form, it is represented as a map of contacts (Figure 2), where a contact is defined as any discrete airborne, surface or subsurface object detected by electronic, acoustic, and/or visual sensors [26]. The term contact report is often used when discussing the

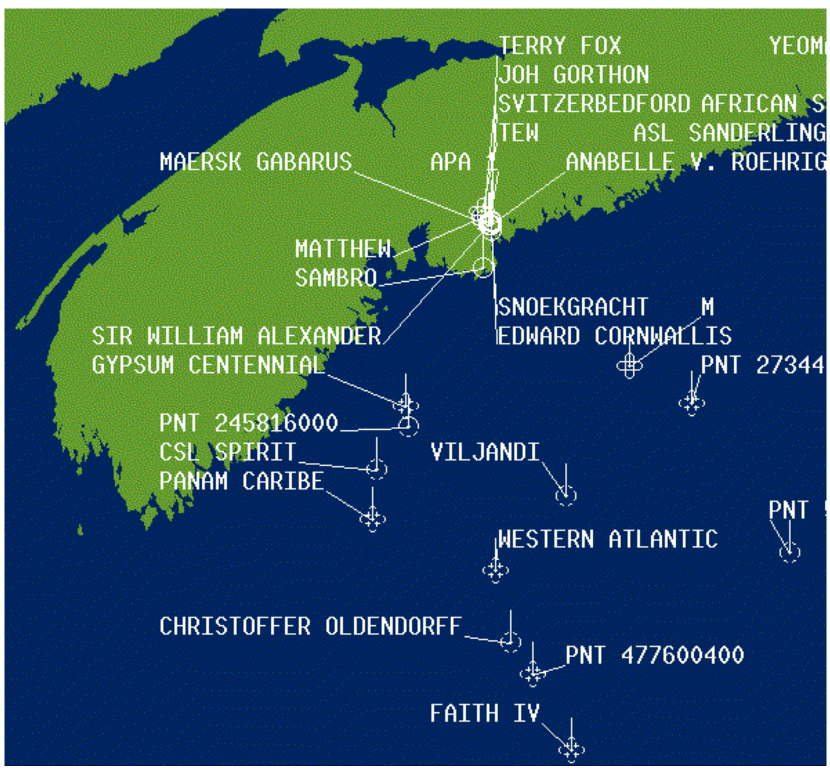

Figure 2: Unclassified example of the Recognized Maritime Picture (RMP) off the coast of Nova Scotia, Canada. Green indicates land while blue indicates ocean. Each contact is indicated using a symbol and descriptive text.

RMP. A contact report is information about a contact at a time of observation, usually containing identity attributes and position. Identify attributes for a ship would include name, flag, the Maritime Mobile Service Identity (MMSI) number, etc. The RMP presents some of this information using visual cues while other information requires “drilling down” into its metadata. This map representation of the maritime situation allows various maritime organizations (e.g., RJOCs, Marine Security Operation Centres (MSOCs)) to develop an understanding of current maritime activities in their Area of Interest (AOI) or Area of Responsibility (AOR).

An identified need for the RMP to convey uncertainty has been recognized through discussions with those who regularly interact with the RMP. The research is being done in multiple phases. Phase one [24] included doing basic research on visualizing uncertainty in an RMP-like environment using human-in-the-loop experimentation to test designs. Non-experts were used in the experimentation. Phase two [25] included an investigation into the usefulness of the designs in an RMP environment using subject matter experts. Subsequent phases will investigate how to rigorously calculate and assign uncertainties to the symbology developed. In the following, the UVDS will be followed to illustrate the research and the usefulness of the UVDS.

3.1 Identify the uncertainty visualization task

Uncertainty present in the RMP data needs to be visually represented for those who use and build the RMP.

Background: In its present form, the RMP does not offer cues as to the uncertainty associated with the data being presented in the RMP. Uncertainty in the RMP can arise from, for example, contact metadata being out of date, wrong or missing; false contact reports; the time-lag for each contact being different; lack of distinction between areas with no contacts as compared to areas with no sensor/information coverage; and variations in the sensor/information coverage due to varying weather, sensor altitude (e.g., when mounted on a plane), ships not reporting as they should, time of day, etc. This underlying uncertainty can mean, for example, that two contacts side by side in the RMP may in reality not be anywhere near each other. This situation is common when the contact positional information have different associated time-lags. It is also easy to wrongly think that the contact report information for each contact is equally believable, and that where there is an absence of a contact, no object exists.

3.2 Understand the data that need to have their uncertainty visualized

Each contact has an associated set of metadata which can include (but is not exclusive to) speed, heading, name, MMSI number, threat, flag, destination, origin, type, cargo and a digital image. Each contact has various degrees of metadata included in its contact report(s). At worst, there is no metadata and all that exists is a position (i.e., there is something at this point in space). At best the metadata consists of all of the above, and perhaps more. The different degrees of metadata are due to the multiple sources of data and information that feed the RMP. These sources include radar, surveillance flights, self reporting systems, voluntary reports, etc., each providing its own set of data and/or information. The data and information being received can be in various formats; e.g., text, numerical, and pixels. An in-depth description of all the data and information feeding the RMP, including the precision to which the data is received and which data are prone to mistakes, is not relevant to this paper. However, we can suggest a fictitious example to illustrate the complexity of the situation and what needs to be accomplished in this step.

Suppose we have a source that provides data to the RMP. This source, known as Source X, automatically reports ship positions and ship names every 30 minutes. Non-commercial fishing vessels and pleasure crafts in Canadian waters are mandated to carry a Source X transmitter. On a clear sunny day, the transmitter needs to be within 100 nautical miles (plus or minus a nautical mile) of a land based receiver for the report to be received. There are 10 such receivers along the east coast of Canada. The range can decrease to 50 nautical miles during rain and snow events. The range also decreases during other inclement weather but no reportable pattern has been observed. The ship position is determined through the global positioning system (GPS) and is exact to within 15 m. The position is reported in latitude and longitude to 1/10000 minute. The name of the ship is typed into the Source X transmitter by personnel on the ship and therefore can be prone to misspelling, shortened versions of the actual name or the name not being changed when the Source X transmitter moves to another ship. Source X reports nothing else about the ship, meaning information such as its destination, vessel type and flag are unknown. The dynamic information, such as average speed and heading, can only be approximated by receiving multiple reports. The Source X receivers send the data to the centres responsible for creating the RMP (e.g., the RJOC) via Ethernet, as soon as the receiver receives a report. The reports are not in a format that can be automatically inputted into the RMP database; therefore, the data need to be transformed into the proper format when they arrive at the RJOC. The time-delay between a Source X report being sent by the transmitter and then finally inputted into the RMP database is approximately 10 minutes.

The RMP has a vast amount of data and information of various types from various sources. The above only describes one fictitious data source, but illustrates the potential complexity of the RMP data. The UVDS step of understanding the data is useful because it reminds (and requires) the designer to become familiar with the collection methods and the types of data. The designer must have this knowledge in order to appropriately identify, calculate and visualize the uncertainty as well as explain the primary data to which the uncertainty is related.

3.3 Understand why uncertainty needs to be visualized and how the uncertainty visualization needs to help the user

In the case of the current RMP, there is nearly nothing to signal to the viewer that there is uncertainty in what they are viewing (e.g., see Figure 2). An RMP with none of the uncertainty in its contacts displayed looks like all the information is current, all the ships are currently in the positions displayed on the map, all the information comes from sources that never have mistakes, and the entire area is monitored by sensors feeding the RMP. However, understanding the uncertainty in the picture would be useful for those maintaining the RMP (i.e., the operators), for those trying to understand the picture, and for those doing analysis tasks based on its content. For example, for an informed decision to be made regarding the RMP, whether it is regarding where to send a surveillance asset, how to prioritize the order a group of ships should be investigated, etc., more information on the uncertainty surrounding the contacts in the RMP needs to be known. While the uncertainty levels can be determined by investigating each contact one by one, that is a time consuming process if there are more than a few ships to be investigated. Having a visual representation of the uncertainty overlaid onto the RMP can help a decision maker quickly assess a situation and, if necessary, decide on which contacts or areas are worth a closer look before a decision is made. The uncertainty visualization needs to give those who use and build the RMP the ability to quickly understand the uncertainty in the RMP with minimal cognitive effort.

3.4 Decide on the uncertainty to be visualized

Discussions with those who work with the RMP identified three primary uncertainties which require visualization: uncertainty due to the passage of time; uncertainty in position; and uncertainty in identity (i.e., who the contact is).

Every piece of RMP metadata has uncertainty. Without this step to narrow down the potentially useful uncertainty to be visualized, effort could be wasted trying to visualize unimportant uncertainty.

3.5 Decide on a definition of uncertainty

Based on the definition given in Plewe [23], uncertainty was defined as follows: **uncertainty is the dissimilarity between a given representation of reality and the known or unknown reality**, where the unknown reality simply means you do not know what the reality actually is that you are representing.

This is a broad definition that incorporates many definitions of uncertainty. It was an appropriate definition for the task at hand. Without this step, someone may assume that the uncertainty being represented includes, for example, “feelings” of uncertainty. It does not, unless those feelings are based on provable observations of dissimilarity between reality and the representation of reality.

3.6 Determine the specific causes of the uncertainty

Uncertainty in the RMP may be specifically caused by the time between source reporting; precision and accuracy of the data; information, data and/or metadata being wrong or missing, human or machine error; false contact reports; malfunctioning information or data source; the geographical area not being surveyed either recently or at all; the weather; ships not reporting as they should; time of day; changes in attributes of the contact between reports; etc. The causes of uncertainty in the RMP have the potential of being the cause of uncertainty due to the passage of time, uncertainty in position and uncertainty in identity, identified in Section 3.4 as the uncertainty to be visualized.

Note that uncertainty due to the passage of time and uncertainty in position are partially linked. Part of the uncertainty in position is due to the passage of time, combined with the uncertainty in the speed and in the direction of the ship. Uncertainty in position can also be caused by the reliability, the precision and the accuracy of the source of the information.

This step illuminates the many causes of uncertainty present in the RMP data and therefore the potential causes of the uncertainties the designers wish to focus on, which is important for the designer to understand. It also provides the designer needed information for later calculating the uncertainty in preparation for visualization.

3.7 Determine the causal categories of the uncertainty

Based on Table 1, the (collective) causal categories of the three uncertainties to be visualized are Data Acquisition Limitation (e.g., GPS measurement accuracy); Data Acquisition Error (e.g., mistyping information); Phenomenon Discretization (e.g., position of a moving ship); Noise; Ambiguous Data (e.g., using the short form for a ship name); Data Age; and potentially Data Corruption and Misinterpretation.

This step helps categorize the specific causes of uncertainty identified in the previous step into much more manageable groupings. These groupings also help the designer understand the generalized problems associated with the data, and potentially aid in the design of more general solutions.

3.8 Determine the visualization requirements

For this application, the visualization should give the audience enough information to make an educated decision on whether to obtain more information about a contact, group of contacts or area. The audience must be able to distinguish between degrees of uncertainty but there is no need for the audience to be able to extract the values of the uncertainty from the visualization. The uncertainty representation is to be presented in conjunction with the contact symbols and must not overwhelm the contact symbol or distract from it. The uncertainty representation must also avoid using characteristics, such as the colour red, that might have unintended meanings associated with them. Clutter should also be minimized. The following is a modified list of the visualization requirements stated in [24]:

- The uncertainty representations must not (unintentionally) interact with each other.
- Each uncertainty level must be uniquely understood and not rely on the presence of other uncertainty levels.
- The visual characteristics must maintain their ability to be discriminable under a range of ambient lighting conditions.
- The use of colours and symbols must not conflict with RMP symbology.
- The representation must be understood immediately without requiring additional actions.
- The size of the symbology must be appropriate for the zoom level.
- The meaning of the coding must not require the operator to rely on long term memory or consult supplementary information sources.
- Wherever possible, the coding should conform to existing psychological constructs and stereotypes.
- Simpler symbol designs are preferred over more complex designs.

- Use of alphanumeric characters is not preferred.
- Blinking or flashing symbology encoding must not be used.
- Use of blurring of symbols (e.g., [6]) must be avoided.

This step is indispensable to ensure that the visualization is useful and practical. The physical environment in which the RMP is used and maintained, as well as in what way the RMP is used, maintained, and represented, must be taken into consideration.

3.9 Prepare the uncertainty for visualization

For the initial phase's experimentation, the uncertainty levels were assigned randomly because the objective of the experiment was to test the initial symbology (1. & 2. below) and thus did not require a more comprehensive assignment of uncertainty values. Then, in phase two of the investigation, the uncertainty levels were assigned using observed source reliability and how operators treat data based on age (3. & 4. below). A complete calculation of the uncertainties of the data being looked at is a non-trivial exercise. Finding rigorous ways to calculate the uncertainties of interest is a future phase of this work.

This step is essential for creating an uncertainty visualization. The choice to avoid explicitly calculating uncertainty at this moment in the research allowed the research to progress without being obstructed by the complexity of the uncertainty calculations.

3.10 Try different uncertainty visualization techniques and get audience opinions and criticisms

(Due to the loop between the final two tasks, they will be treated in one subsection.)

1. At first, in phase one, the "audience" were those working on this project: two defence scientists from Defence Research & Development Canada (DRDC) and the team of contractors from Human*systems* Inc. (HSI) [24]. Different visualization techniques were designed and then the audience would give their opinions and criticisms. There were many iterations of this cycle before a final set of visualizations were developed for formal testing.

   The final set is shown in Figure 3 and are labelled the Lego[1] Design and the Rectangle Design for convenience. The visualization requirements of Section 3.8 greatly limited the design options of the uncertainty representation. The size of the RMP contact symbols, which are of the order of 5 mm on the RMP operator's computer monitor (much smaller than shown in Figure 3), was arguably the biggest limiter of potential options. Uncertainty in identity is represented by the colour of the blocks (Lego Design) and the rectangle (Rectangle Design). Uncertainty due to the passage of time is represented by the number of vertical blocks (Lego Design) or the position of the black circle (Rectangle Design). Uncertainty in position is represented by the number of horizontal blocks (Lego Design) or the radius of the black circle (Rectangle Design).

[1] This was a label of convenience based upon the similarity of the design to LEGO building blocks and is not associated with the registered trademark of The LEGO Group.

As the uncertainty representations merely needed to cue the viewer to the presence and extent of the uncertainty, the team chose to use colour, spatial position and size to represent levels of uncertainty. For each aspect, (i.e., identity, time and position) there were three levels of uncertainty that could be represented. The colour coding used to represent uncertainty in identity uses a modified traffic signal convention; however, the colour red could not be used due to conflicts with other colour coding in the RMP. In the Rectangle Design, the team also chose to represent temporal uncertainty increasing from left to right because there was no clear convention as to whether increasing left to right or right to left would be more intuitively understood. The team also chose to represent increasing positional uncertainty with increasing horizontal blocks (Lego) and dot diameter (Rectangle) to emulate the already established convention that big error ellipses around a position means large uncertainty.

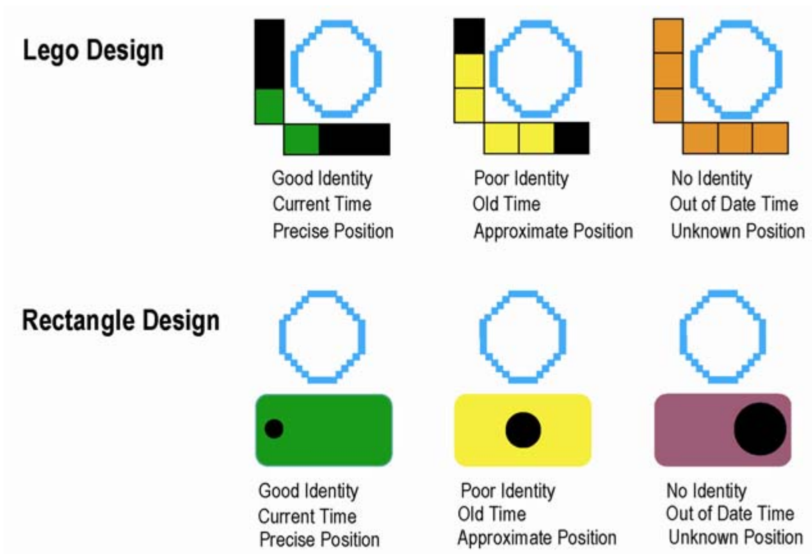

Figure 3: An enlarged example of the two designs of uncertainty symbology tested in phase one of the RMP research. The blue octagon represents the contact. Uncertainty in identity is represented by the colour of the blocks (Lego Design) and the rectangle (Rectangle Design). Uncertainty due to the passage of time is represented by the number of vertical blocks (Lego Design) or the position of the black circle (Rectangle Design). Uncertainty in position is represented by the number of horizontal blocks (Lego Design) or the radius of the black circle (Rectangle Design). Figure taken from [24].

2. The next set of audience members were formal experiment subjects, as described in [24]. The experiment tested the uncertainty visualization symbology using a combination of training, timed taskings, and surveys. This concluded phase one of the work. Accuracy was high for both designs, with no significant differences between them.

3. In phase two [25], the audience members were initially made up of members of DRDC and HSI who were working on the project. The symbology used in the previous experiment was imported into another environment, Google™ Earth (GE), since many other operator tools are now being released in GE. There were certain aspects of the symbology that needed to be

altered, such as colour, weight of lines, size, etc. Several iterations of opinions and criticisms were required to come up with a satisfactory symbol set in this new environment. A partial example is shown in Figure 4.

4. The next set of audience members were subject matter experts (SMEs); i.e., those who use and maintain the RMP. These were again formal experimental subjects. They were given training and then tasks to accomplish using the visualizations decided upon in the previous step. A questionnaire was also administered. The results helped gauge the usefulness of the symbology. The pattern of the SME performance data was very similar to the pattern from the previous experiment with the non-experts. The subjective questionnaire evaluations showed strong support for the usability of the aids and there was general belief that they would add to operational capability.

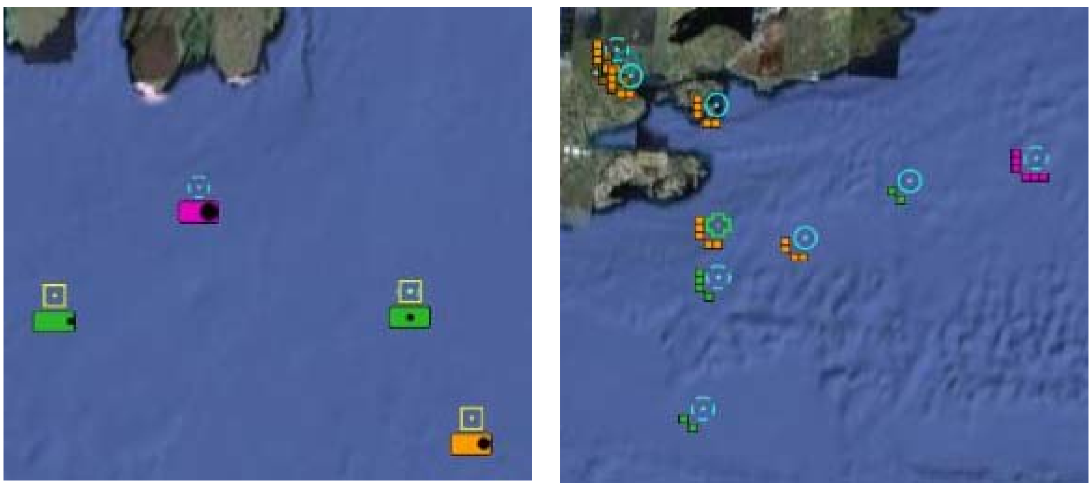

Figure 4: Examples of the symbology imported into Google™ Earth, appearing with contact symbology.

The final two steps in the strategy built upon all the previous steps. The steps were essential in narrowing down potential visualizations and judging them with respect to the RMP. The next step in this research will be to revisit “prepare the uncertainty for visualization” and determine some rigorous methods to dynamically calculate the uncertainty that feeds the symbols.

3.11 RMP application remarks

Section 3 has shown that the UVDS provides a systematic method to design uncertainty visualizations. The large number of data and information sources continuously feeding the RMP result in an abundance of uncertainty being imbedded in the RMP. The RMP example shows how each step can help navigate the designer towards producing a useful uncertainty representation by requiring them to complete the eleven steps. It has also been shown here that following the steps to document the work can help explain the research.

4 Concluding Remarks

The strategy discussed here has been created specifically to help the designer better understand what steps need to be accomplished to produce uncertainty visualizations. The eleven steps are all logical and practical steps that may have been addressed naturally by a designer who is unaware of the UVDS. There is benefit to formalizing the steps both for the novice and experienced designer. For the novice, the steps provide documented guidance for understanding the process to be followed. For the experienced designer, it provides reminders for steps which should be explicitly thought about. In addition, each finished step could serve to help document a finished product, which can be used when discussing or justifying a design or giving in-depth background on the visualization, as shown in Section 3.

Further work on the UVDS would be to incorporate changes suggested by the users of the strategy. UVDS could also be augmented as formal uncertainty visualization theory is developed, thus providing guidance on what uncertainty visualization techniques to implement given the type of uncertainty to be visualized (e.g., [8]). Meanwhile, the UVDS could work in conjunction with existing theories, postulates and frameworks.

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List of symbols/abbreviations/acronyms/initialisms

AOI	Area of Interest
AOR	Area of Responsibility
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
GE	Google™ Earth
GPS	Global Positioning System
HSI	Human*systems* Inc.
MDA	Maritime Domain Awareness
MMSI	Maritime Mobile Service Identity
MSOC	Marine Security Operation Centre
R&D	Research & Development
RJOC	Regional Joint Operations Centre
RMP	Recognized Maritime Picture
SME	Subject Matter Expert
UVDS	Uncertainty Visualization Development Strategy

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(U) Visualizing uncertainty can be a challenging endeavour. In an attempt to minimize the challenges, this paper defines a systematic approach to designing a visual representation of uncertainty called the Uncertainty Visualization Development Strategy (UVDS). The strategy helps in the understanding of both the data and the uncertainty. The UVDS has eleven steps which include: identify the uncertainty visualization task; understanding the data that need to have their uncertainty visualized; understanding why uncertainty needs to be visualized and how the uncertainty visualization needs to help the user; deciding on the uncertainty to be visualized; deciding on a definition of uncertainty; determining the specific causes of the uncertainty; determining the causal categories of the uncertainty; determining the visualization requirements; calculating, assigning, or extracting the uncertainty; trying different uncertainty visualization techniques; and obtaining audience opinions and criticisms. The UVDS has been created specifically to help the designer produce comprehensive uncertainty visualizations, allow the designer more time to focus on the creative aspects of the work, and give those trying to understand what is behind the design a clearer understanding. As an example application of the UVDS, it is applied to current research regarding uncertainty visualization for the Canadian Recognized Maritime Picture (RMP).

(U) Visualiser l’incertitude peut être une entreprise extrêmement difficile. Afin de minimiser les difficultés, le document ci joint propose une approche systématique pour la conception d’une représentation visuelle de l’incertitude : la Stratégie de visualisation de l’incertitude (SVI). Cette stratégie aide à comprendre les données et l’incertitude qui s’y rattache. La SVI comporte 11 étapes : définir la tâche de visualisation de l’incertitude; comprendre les données dont l’incertitude doit être visualisée; comprendre pourquoi l’incertitude doit être visualisée et comment cette visualisation aidera l’utilisateur; décider de l’incertitude à visualiser; donner une définition de l’incertitude; déterminer les causes précises de l’incertitude; déterminer les catégories causales de l’incertitude; déterminer les besoins en matière de visualisation; calculer, attribuer ou extraire l’incertitude; essayer différentes techniques de visualisation de l’incertitude; et recueillir des opinions et des commentaires critiques. La SVI a été créée spécifiquement pour aider le concepteur à produire une visualisation complète de l’incertitude, pour permettre au concepteur de consacrer plus de temps aux aspects créatifs du travail, et pour aider les intéressés à mieux comprendre le système de visualisation. Exemple d’application : la SVI est utilisée dans les recherches en cours sur la visualisation de l’incertitude pour le Tableau de la situation maritime (TSM) du Canada.

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(U) uncertainty; Information Visualization; design; methodology; RMP; Recognized Maritime Picture

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