Graphic Representations of Uncertainty Within Sub-surface Environments

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Abstract

Past research has demonstrated that submarine operators provide more accurate range estimates when presented with a graphical representation of the uncertainty surrounding a target's spatial location. The primary aim of the present study was to examine what sort of representation of uncertainty leads to the best performance. In particular, we compared participants' decision-making performance when presented with representations that varied across six conditions (50%, 75%, 95%, 99%, no ellipse and tabular non-graphical). Participants were presented with each of the uncertainty representations in six different scenarios that were either all classified as easy or difficult based on standard objective tracking measures. Spatial knowledge was assessed during each scenario through range to target estimates, range to target maximum and minimum estimates, confidence intervals and completion time measures. It was found that using ellipse representations lead to better decision-making, and there was some evidence that large 99% and 95% confidence intervals resulted in the best performance.

Introduction

The present study focused on tactical and strategic decision-making in sub-surface (underwater) environments. While the goal of any complex system is to facilitate the development of situation awareness in its operators, several factors hinder the completion of this goal within sub-surface environments or, more specifically, systems used by operators within submarines. Within such environments and systems, numerous sources of uncertainty cloud the operator's ability to process and use information with any significant degree of confidence and certainty. This, in turn, hinders the operator's development of situation awareness.

Schunn, Kirschenbaum and Trafton (2003) believe the major source of uncertainty in submarine sonar arises because operators attempt to compute the course, speed, and range to the noise source from a passive signal, which provides measurements for only two parameters: bearing (direction) and bearing rate (rate of change in the bearings). Thus, passive sonar fails to provide submarine operators any range-to-target information. Without any range information, an infinite number of course, range and speed combinations exist that are capable of producing the identical signal. With an infinite number of combinations, the system's capability to pinpoint a target's position with any real certainty is severely hindered.

When a submarine receives a passive sonar signal, the Commanding Officer (CO), in collaboration with their team, must determine where the signal is emanating from and how to respond. The CO uses the available information acquired from the raw sonar signal and the computer analysis of that signal to make a global response choice (i.e., attack, surveillance, or retreat). As time is a critical factor during military operations, the CO is required to act quickly on the basis of a collection of ambiguous and uncertain information in order to make decisions. Despite the CO's constant need to make such critical decisions, there are few visualization tools available to submarine operators for representing the various forms of uncertainty they encounter.

Using experienced Naval Submarine Officers, Kirschenbaum and Arruda (1994) began to investigate sub-surface uncertainty by examining the performance effects of graphic and verbal representations of target position uncertainty in eight different scenarios that varied in difficulty due to manipulated oceanic conditions. Their research demonstrated that submarine operators provide more accurate range estimates when presented with a graphical representation of the uncertainty surrounding a target's spatial location.

Kirschenbaum and Arruda (1994) reported that the most striking feature of their results was the contrast between submariners' performance in the high (difficult task) and low (easy task) noise scenarios. Specifically, in comparison to decision-making performance in difficult scenarios with high oceanic noise, other, well-learned strategies were sufficient to produce the same level of performance as that achieved with the uncertainty ellipse during the relatively easy scenarios of low oceanic noise. This suggests that the uncertainty ellipse visualization was only effective when the task was too difficult to be solved without the aid. This unexpected task difficulty distinction led Kirschenbaum and Arruda to emphasize the need for further research to "explore the perceptual and cognitive elements" (p. 417) of the uncertainty ellipse, such as the degree to which the effects of the ellipse vary as a function of task difficulty, ellipse characteristics, and expertise of the operator.

The primary aim of the present study was to act on Kirschenbaum and Arruda's (1994) suggestion and to extend their findings by examining what sort of representation of uncertainty leads to the best overall performance. In particular, participants' decision-making performance when presented with graphical representations that varied across five different uncertainty ellipse conditions (50%, 75%, 95%, 99%, no ellipse) and one tabular non-graphical condition was compared. In accordance with Kirschenbaum and Arruda's findings, task complexity was also manipulated to examine these various conditions under easy and difficult conditions. The uncertainty ellipses provided participants with a graphical display of the area of uncertainty (i.e., range x bearing probability distribution) associated with the target's spatial location. As scenarios progressed, additional target related

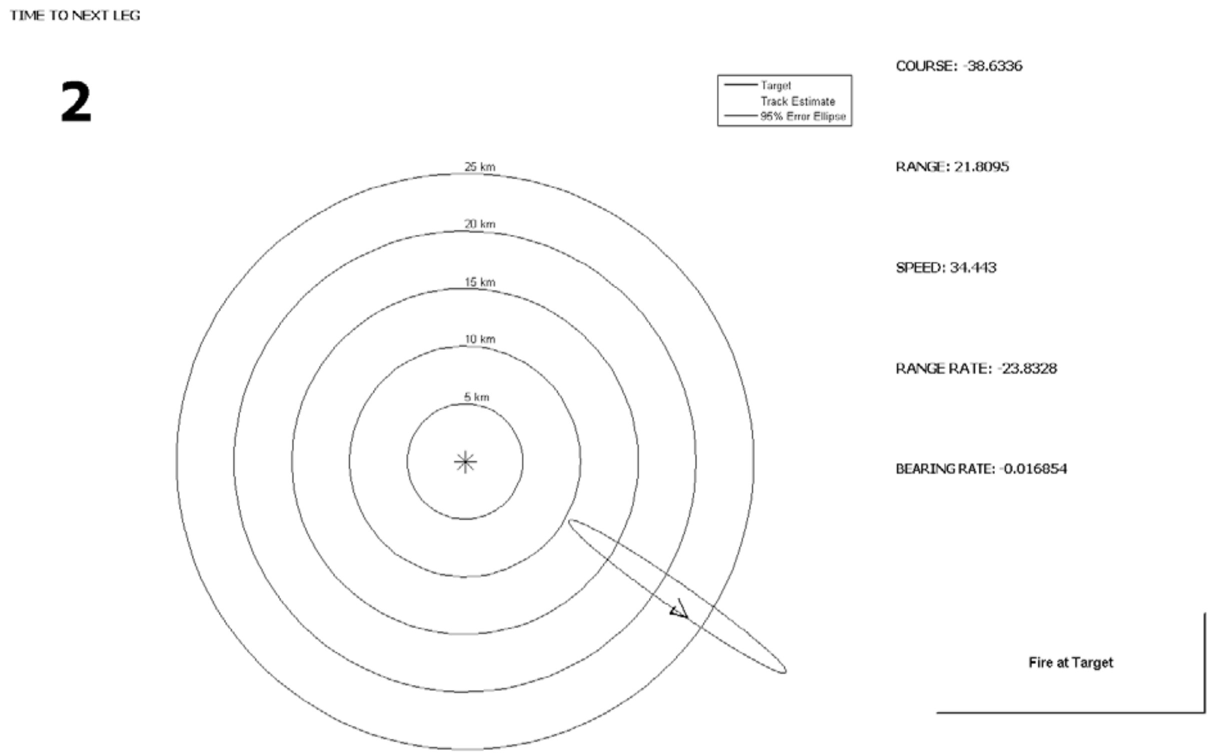

Figure 1: The experimental interface. This screen shot displays a 95% ellipse with six seconds to go before the completion of the first of six 32-second stages. The Target Information Window on the right-hand side contains estimates relating to the enemy submarine. The * symbol represents the own-ship, and is permanently in this middle position. The dot (located approximately 23km North-East from the own-ship) represents the algorithm's estimate of the enemy's position, with the associated ellipse representing the uncertainty surrounding that estimate.

information was collated and analyzed, resulting in the uncertainty ellipse gradually decreasing in size over time.

Method

Participants

Twenty-four Adelaide University undergraduate students (eighteen male, six female) with ages ranging from 18 to 51 years (*M* = 27 years, 2 months, *SD* = 9 years, 5 months) voluntarily participated in the experiment. Participants were randomly assigned to one of two task complexity groups: 'easy tracking scenarios' and 'difficult tracking scenarios'.

Apparatus and Materials

Thirteen scenarios (twelve experimental and one practice) were programmed using Matlab Version 7. The scenarios were presented on a TPG Personal Computer running at 2800MHz, and were displayed on a 19-inch monitor with screen resolution set at 1024 x 768 pixels.

Target and own-ship information (course, range, speed, etc.) for each point throughout the scenario was generated using a Track Motion Analysis (TMA) algorithm. The simulation parameters included the own-ship speed (5 knots), own-ship to enemy contact range (15 kilometres), and the enemy contact speed (12 knots). The parameters stipulated for the algorithm were an own-ship to enemy contact starting range (20 kilometres, *SD* = 5 kilometres), and an enemy contact speed (15 knots, *SD* = 4 knots). For each scenario, thirty bearing measurements were collected (one every six seconds) for the entire duration of the scenario. In addition, the own-ship executed a maneuver (leg) during time periods 13 and 17.

Each scenario was designed to run in Matlab's Graphic User Interface (GUI). Figure 1 shows a screenshot of the experimental interface used in all seven scenarios, with only the size and visualization of the ellipse varying. This display provided participants with a geographic planar view of the target enemy in relation to the own-ship, which always remained in the centre. Permanent 5km range rings encircling the own-ship were incorporated into the interface to provide participants with an easily interpretable scale, while also providing greater meaning to the size of the ellipse. With each update and change of the target's position a thin black line was drawn to provide participants with a tracking or movement history display. Participants were also provided with a Target Information Window (the table-like information located on the right hand side of Figure 1), which continually updated the enemy contact's estimated course, range, speed, range rate and bearing rate.

When participants were presented with one of the four ellipse conditions (50%, 75%, 95% and 99% uncertainty ellipses), the interface also contained the respective confidence ellipse around the estimated enemy's position. The ellipse provided participants with a graphical display of the area of uncertainty (i.e., range x bearing probability distribution) associated with the target's spatial location. As scenarios progressed more target related information was collated and analyzed, resulting in the uncertainty ellipse gradually decreasing in size over time.

In the no-ellipse condition, the interface was similar to that shown in Figure 1, with the only difference being the omission of any visualization of the uncertainty. Instead of displaying the target and its respective uncertainty ellipse, during this condition only the target (a green dot) was visualized.

In the tabular non-graphical condition participants were not presented with any graphic visualization of the scenario, but were only presented with the Target Information Window. Participants completed the scenario using 'Time to Next Leg', 'Course', 'Range', 'Speed', 'Range Rate' and 'Bearing Rate' information only.

Design

To determine whether uncertainty ellipses with varying degrees of certainty affect the ability to make decisions within differing submarine conditions a six (uncertainty ellipse: 50%, 75%, 95%, 99%, no ellipse, tabular non-graphical) by two (task complexity: easy tracking, difficult tracking) mixed experimental design was implemented, with ellipse conditions the within-subjects independent variable, and task complexity the between-subjects independent variable.

To distinguish between 'easy' and 'difficult' conditions in the task difficulty manipulation, each scenario and the algorithm's tracking performance was examined. The six easy scenarios were those where the true location of the enemy contact was within 4000 metres of the estimated position at time period 15 (i.e., the half-way point of each scenario), and within 2000 metres at time period 30 (i.e., the completion of scenario). In comparison, the six difficult scenarios were those in which the distance between the true and estimated enemy's position was greater than 6000 metres at time period 15 and 5000 metres and time period 30.

Procedure

Upon arrival, participants received some background information on how the nature of the submarine environment fosters uncertainty and the underlying reasons submarine operators use passive sonar to estimate a target's position. Participants were further informed that the present study examined the use of ellipses as a representation of the area of uncertainty that surrounds the precise location of an enemy contact. It was explained that a 95% ellipse means that the enemy contact is within the spatial ellipse 95% of the time, and is out of the specified area only 5% of the time, while a 50% ellipse implies that the target is within the specified area only half of the time. Participants were then informed that as time goes by, passive sonar collects more information via further readings which therefore assist to increase the certainty of the target's position, consequently reducing the size of the uncertainty ellipse.

Participants then completed an initial practice session designed to provide familiarity with the scenario format, and to provide a concrete example of a randomly selected uncertainty ellipse. In addition, this practice scenario was intended to control for individual differences in keyboard proficiency. During the practice session participants were allowed as much time as they felt necessary. Participants were also encouraged to ask questions in the practice scenario. The first of six experimental scenarios only commenced at the completion of the training session and when all questions had been answered to the participant's satisfaction.

Prior to each experimental scenario participants were read the following instructions and mission statement:

Instructions This scenario contains six possible stages, but you are instructed to use only as many as you feel necessary. The total duration of each stage is 32 seconds. When you are ready to give the order to fire, you are instructed to select the 'Fire at Target' button and may select it at any time during the scenario. At the completion of each stage, you will be asked several questions regarding the enemy contact's spatial location, and whether you wish to fire at the target, or continue on to the next stage. Like submarine operations in the real world, time is a critical factor, so do not continue to collect information longer than you feel the need.

Mission "The current situation is classified as 'hot war'. You are the Commanding Officer of the HMS Elliot Submarine and are under direct orders to monitor and attack any hostile contacts. Your superior officer has indicated that no subsurface friendlies are expected within your patrol area during the next 24 hours, but a Delta (enemy submarine) has been spotted within your patrol area. All data about the enemy submarine is available in the Target Information Window, which continually updates as the scenario progresses".

.	Mean Absolute Error (metres)	Final Absolute Error (metres)	Range Estimate Confidence	Completion Time (seconds)	Mean Decision Time (seconds)
50% Ellipse					
EASY	3943 (1373)	2385 (1677)	3.56 (1.49)	209.5 (98)	36.6 (9.6)
DIFFICULT	6114 (2292)	8876 (3035)	4.01 (1.26)	180.4 (61)	37.6 (10.7)
75% Ellipse					
EASY	3469 (1874)	2492 (3198)	3.5 (1.51)	224.1 (94.3)	37.5 (9.8)
DIFFICULT	7717 (2956)	8258 (3286)	4.32 (1.32)	182.9 (51.6)	37.5 (11.5)
95% Ellipse					
EASY	3838 (1214)	3420 (3203)	3.48 (1.55)	211.9 (131)	35.3 (9.7)
DIFFICULT	6272 (2006)	7116 (3094)	4.19 (1.67)	231.1 (99.5)	42 (21.7)
99% Ellipse					
EASY	3807 (2314)	3648 (3536)	3.64 (1.58)	236.8 (128.4)	38.3 (14.5)
DIFFICULT	8463 (3061)	7826 (2888)	4.35 (1.65)	224.6 (114.7)	36.2 (14.2)
No Ellipse					
EASY	6820 (10364)	3947 (3699)	3.39 (1.85)	238 (127)	38 (7.7)
DIFFICULT	7936 (3727)	8517 (6179)	4.15 (1.76)	173.9 (111.3)	34.7 (8.9)
Tabular Non Graphical					
EASY	3726 (1907)	1515 (1129)	2.97 (1.46)	204.9 (94.2)	34 (10.3)
DIFFICULT	7511 (2587)	7854 (2753)	4.36 (1.75)	191.7 (113.9)	36.4 (21.1)

Table 1: Means and standard deviations (parentheses) for mean and final range estimate error, range estimate confidence, scenario completion and decision times.

As task complexity was manipulated between-subjects, those participants randomly assigned to Easy Tracking scenarios were further instructed, "the current sea conditions are classified as calm, which is the condition in which sonar readings provide the most accurate tracking estimates. As the sea conditions are favorable, the sonar estimates are likely to be relatively accurate".

Participants assigned to the Difficult Tracking scenarios were instructed, "the current sea conditions are classified as choppy and unpredictable, which are the conditions in which sonar readings provide the least accurate tracking estimates. As the sea conditions are unfavorable, the sonar readings are likely to be relatively inaccurate".

Following these instructions, participants began the first of six experimental scenarios. The order in which the uncertainty ellipse conditions were presented to participants was counterbalanced, as was the pairing of ellipse condition to each of the thirteen scenarios. A rest interval of two minutes was permitted between each test scenario. The experiment was completed once all six scenarios had been run, with completion time ranging from 30 to 45 minutes per participant.

Results

Table 1 shows descriptive statistics for each condition. A series of six (ellipse conditions) by two (task complexity) mixed model ANOVAs were conducted to examine participants' range accuracy, confidence associated with range estimates, and their scenario completion and decision times.

The mean and final (i.e., at the time of fire) absolute range error analyses revealed statistically significant differences in performance for task difficulty comparisons, with participants in the easy scenarios providing more accurate mean range estimates (M = 4267m, SD = 1848m) than those presented with difficult tracking scenarios (M = 7336m, SD = 2096m), F (1,14) = 14.5, p = .002, η^2 = .51. This finding indicates that the task difficulty manipulation was successful.

However, across most ellipse condition analyses there was little difference in performance between each of the six different ellipse conditions. More specifically, the ANOVAs examining the mean and final confidence values (ranging from 1 to 7, where 1 = not very confident and 7 = very confident) for each of the ellipse conditions did not yield any statistically significant differences (Fs < 1). In addition, differences experienced within the various ellipse conditions in the elapsed time from the beginning of the first stage to the point of firing did not reach statistical significance (F < 1). Although not significant, there was a tendency for participants to complete the scenario in less time when presented with the tabular non-graphical condition than a 95% ellipse. A similar pattern of non-significant findings was found in the mean decision time analyses. Specifically, during difficult scenarios there was a tendency for participants to take more time arriving at their range estimates, maximum and

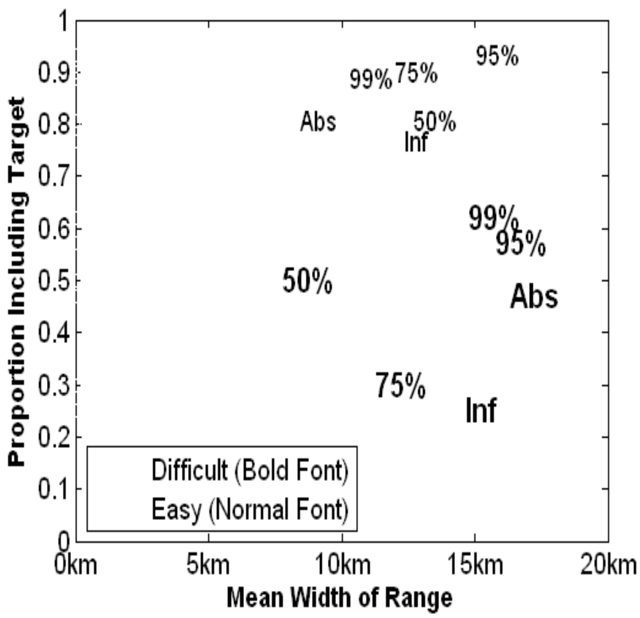

Figure 2: Proportion of participants' maximum and minimum estimates including the true position of the enemy submarine plotted against the mean width of range for all ellipse and task complexity conditions. The 'Abs' refers to the no ellipse condition, and the 'Inf' refers to the tabular non-graphical condition, with all numbers indicative of that particular sized uncertainty ellipse.

minimum estimates, confidence measures and their decision to fire or maneuver when presented with a 95% ellipse in comparison to the no ellipse condition.

Despite these non-significant trends, the most interesting finding followed an examination of the proportion of correct maximum and minimum range estimates. This comparison revealed that the 99% and 95% ellipses were the two best performing conditions at both levels of task difficulty. This outcome is illustrated in Figure 2 where the normal font numbers and letters represent the easy task while the bold and larger characters represent the findings in the difficult scenarios. Examination of the data presented in Figure 2 suggest that the two larger sized ellipse conditions lead to the best interpretation of the uncertainty as participants more frequently knew that the enemy was within a certain distance from their own ship, and provided similarly sized upper and lower range bounds to the other conditions despite having perceptually larger mean widths. Such knowledge of performance can be critically important when confronted with uncertainty surrounding an enemy's position. As demonstrated in Figure 2, the tabular non-graphical condition was the worst performing uncertainty representation because the enemy submarine was correctly located within the participants' range bounds about 77% of the time in the easy tracking scenarios (compared with about 89% in the 99% ellipse), and then deteriorated to 25% when the tracking

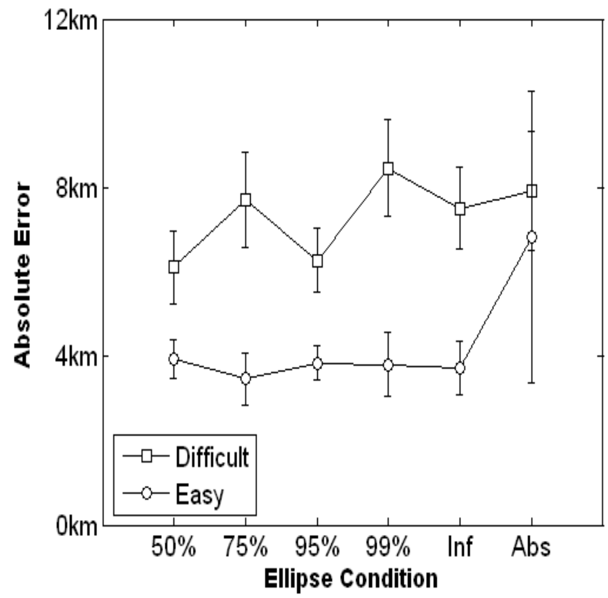

Figure 3: Mean absolute range error for each ellipse and task complexity condition. The error bars represent one standard deviation from the mean.

performance was poor (compared with about 62% in the 99% ellipse).

There was little difference between the six conditions in participant's ability to predict accurately the true range of the enemy submarine, which was especially evident when the task involved easy scenarios. In the case of scenarios with poor tracking performance, the only noticeable fluctuation in accuracy resulted when participants were utilizing a 95% and 50% uncertainty ellipse. Specifically, participants tended to be more accurate with a 95% (M = 6272m, SD = 2006m) and 50% (M = 6114m, SD = 2292m) ellipse than a 99% (M = 8463m, SD = 3061m) and 75% (M = 7717m, SD = 2956m) ellipse representation. These differences in mean and final absolute errors for easy and difficult tasks, and for each ellipse condition are depicted in Figure 3.

Discussion

Graphical representations have been found to be a superior method of visualising the uncertainty associated with a target's position and heading in both aviation (Andre & Cutler, 1998; Cutler & Andre, 1998) and maritime (Kirschenbaum & Arruda, 1994) operations. The present study, however, found little difference between ellipse conditions in performance measures when participants were presented with relatively good performing algorithms in the easy scenarios. Consistent with the findings of Kirschenbaum and Arruda (1994), the general tendency observed in the current study indicated that a difference in performance exists only in the difficult scenarios where algorithm tracking performance was poor, implying that uncertainty ellipses aided performance only when the task was too difficult to complete accurately without the assistance of the uncertainty ellipse.

In military operations, the ability to locate a target accurately within specified upper and lower bounds is critically important. This ability is of greater import if one is able to accurately locate the target within a relatively small maximum and minimum difference as opposed to maximum and minimum estimates at the extreme ends of the scale of interest. Consequently, the finding that participants' provided the highest proportion of maximum and minimum estimates that correctly included the enemy's true position when presented with 99% and 95% ellipses has real-world importance. While the mean range widths were slightly better (i.e., lower) in most of the remaining ellipse conditions, their accuracy, or proportion correctly including the target, was noticeably lower in both easy and difficult conditions. It appears that the two largest ellipses gave participants the best understanding of their environment and the uncertainty surrounding the enemy's position, which suggests that participants possessed a superior level of situation awareness when utilizing these specific ellipses.

Considering the potentially disastrous consequences following a collision during a military operation, the finding that participants exhibited a greater awareness of their current environment, and were more likely to identify the location of the enemy submarine within stipulated bounds when presented with 99% and 95% uncertainty ellipses than the remaining ellipse conditions, possesses considerable real-world importance.

In their study, Kirschenbaum and Arruda (1994) found that during moderately difficult scenarios participants presented with an uncertainty ellipse visualization provided range estimates that were significantly more accurate than those participants provided with verbal uncertainties. In explaining this result, they relied on previous research findings that had indicated the format of information interacts with the type, or structure, of the task at hand. Specifically, in a meta-analysis of eight studies, Vessey (1991) reported that graphic formats led to better performance in spatial tasks, whereas tabular formats result in better performance in tasks that require symbolic processing, such as calculations.

The present study compared the mean and final range estimates for each of the six ellipse conditions under varying task complexity conditions. Although little difference was found between the ellipse conditions when participants were presented with easy scenarios, the general tendency observed for difficult scenarios suggested that 95% and 50% ellipses were the best performing ellipse conditions for estimating the true range of the enemy. Consistent with Vessey's (1991) report, it appears possible that the potential for any uncertainty ellipse to elicit superior mean range estimates was hindered by the similarity of the tabular-non-graphical condition to the calculation style task of providing a range estimate. In other words, one possible reason the superior performance of the ellipse evident in Kirschenbaum and Arruda's study was not replicated here is that the nature of the scenario was not entirely spatial. Although the ellipse is a spatial cue that is intuitive and one that requires minimal processing, it appears that the display of the target's estimated characteristics in a tabular format used in the tabular non-graphical and no ellipse conditions was adequate to derive a similarly accurate range estimate.

There is considerable scope for future research. Specifically, further investigation into increasing the number of targets and their ellipses is proposed. Of particular interest is to examine how humans perform when required to track and monitor several overlapping and cluttered contacts across a variety of ellipse sizes. The findings of such an investigation may have implications in the design of future uncertainty visualization displays. For instance, as Endsley, Bolte, and Jones (2003) point out, there may be an inherent trade-off between the visualization of the uncertainty, and the detrimental effects of display clutter.

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