POAC'25
St. John's,
Newfoundland and
Labrador, Canada

Proceedings of the 28th International Conference on
Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

User-centred Analysis to Inform the Development of Ice Navigation Decision Support Technologies

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ABSTRACT

A growing interest in northern shipping routes and the transition to autonomous shipping has created an influx of decision support systems and low-level automation technologies for navigation crews in sea ice. While these technologies are intended to support decision-making, they often cause frustration for crews. Researchers theorize that using a user-centred design approach will lead to technologies that are more effective in supporting crew decision-making. This research aims to provide user-centred insights to inform the development of future ice navigation decision support technologies. The study reports a thematic analysis of unstructured interviews conducted with crew onboard a Canadian Coast Guard icebreaker. The interviews focused on the question: How do navigators decide on route planning and navigation in sea ice? The thematic analysis codes are used to create a Hierarchical Task Analysis (HTA) that models the process of route planning and ice navigation onboard this vessel. The HTA is used to identify potential issues and areas where technology can better support ice navigation decision-making.

KEY WORDS Ice Navigation; User-Centred Design; Decision Support; Technology Development

INTRODUCTION

Sea ice navigation is a complex task involving the consideration of many pieces of incomplete information about dynamic environmental variables (Snider, 2012). The consequences of a poor decision can be significant, leading to structural damage or a ship becoming stuck in ice. Experienced ice navigators hold knowledge that enables them to plan routes and make in-situ decisions (Musharraf, et al., 2023). However, technological advances are changing the task of navigation (Mallam, et al., 2020; Lundh, et al., 2024). The development of navigational technologies to support decision-making is being driven by an interest in northern shipping routes and the transition to autonomous shipping (Munim, et al., 2022; Yang, et al., 2024). Ironically, these technologies that aim to support decision-making instead frustrate crews because they are not integrated into the existing system, unreliable, difficult to use, and add complexity to the already complex task of navigation (Lundh, et al., 2024). Research such as Aylward, et al. (2021) and Smith, et al. (2020) theorizes that using a User-Centered Design (UCD) approach to technology development will lead to technologies that are more effective in supporting crew decision-making. However, there has been little research on the application UCD for the development of technologies related to navigation in areas of sea ice (Hsieh, et al., 2024).

This research aims to be the basis for the UCD of technologies to support ice navigation decision-making. It centers on the following questions:

1. How do navigators decide on route planning and navigation in sea ice?
2. How can technology support navigators in route planning and navigation in sea ice?

To address these questions, a thematic analysis and Hierarchical Task Analysis (HTA) were conducted based on interviews with the crew of a Canadian Coast Guard (CCG) icebreaker. The interview transcripts (Tran and Veitch, 2024) included data on several ship ice operations, such as towing and breakouts. However, this paper focuses only on insights related to navigation in sea ice. For the purposes of this paper navigation in sea ice is defined as the actions taken by the bridge crew to plan and follow a route through areas where sea ice is present.

METHODS

Data Source

In February 2024, a research team spent four weeks on a CCG icebreaker operating in the presence of sea ice at the Strait of Belle Isle off the west coast of Newfoundland (Tran and Veitch, 2024). The field research included unstructured interviews with nine crew members. The purpose of the interviews was to investigate the process of route planning and ice navigation on board the vessel. The data report included researcher observations and interviewee experience questionnaire responses.

The roles of interviewees on the vessel included captain, chief officer, first officer, second officer, third officer, and cadet (Tran and Veitch, 2024). Table 1 summarizes the interviewee demographics and ice navigation experience based on questionnaire responses. The responses demonstrate a range of experience amongst the crew including ice navigation experience from less than one year to over 30 years. Types of experience in navigational operations ranged from only observing to watchkeeping, maneuvering, and towing or emergency response.

The name of the CCG icebreaker was not included in Tran and Veitch (2024). Based on interview responses it was inferred that the vessel was about 100 meters long and had a higher ice class then other vessels in the area. It had three diesel engines and could be operated in both revolution per minute (RPM) and power mode. The vessel had fixed pitch propellers and a big rudder. It was equipped with a bubbler system and ice radar, and had recently become Electronic Chart Display and Information System (ECDIS) compliant.

Table 1. Interviewee demographics and experience

Criteria	Demographic	Number of Responses
Year of Birth	2000s	1
	1990s	6
	1980s	0
	1970s	2
Gender	Female	2
	Male	7
	Non-binary	0
Years of Experience in Ice	1 or less	3
	2 to 10	4
	10 to 20	1
	20 to 30	0
	More than 30	1
Type of Ice Experience	Only observing	2
	Watchkeeping and maneuvering	4
	Watchkeeping, maneuvering, and towing or emergency response	3
Arctic (north of 60) Experience	No	2
	Yes	7

Thematic Analysis

Interview transcripts were analyzed using Braun and Clarke’s (2006) six phase approach for reflexive thematic analysis. Braun and Clarke’s approach provided a systematic method for finding insights from the qualitative data source (Braun and Clarke, 2023). A reflexive analysis was chosen to allow for researcher interpretation of latent codes (Byrne, 2022). Latent codes describe implicit rather than explicit meaning. Previous applications of thematic analysis in the maritime domain include Aylward, et al. (2022) and Lundh, et al. (2024).

Based on Braun and Clarke’s (2006) phases and updated literature on the use of thematic analysis (Braun and Clarke, 2023; Braun and Clarke, 2013; Byrne, 2022; Morriss, 2024), the phases used in this analysis were:

1. Data familiarization: The interview transcripts were reviewed and notes were taken about initial observations and possible codes.
2. Data coding: A list of codes was generated based on the notes taken in phase 1. Codes represented interesting features and patterns in the transcripts. Transcripts were then collated by code in a table.
3. Generating initial themes: A map of the codes by theme was created to identify initial

themes. The codes were then collated by theme.

4. Reviewing and developing themes: The interview transcripts and collation of data by theme were analyzed to verify the themes in relation to the transcripts and identify if any themes were missing.
5. Refining, defining, and naming themes: The specifics of each theme were refined and named to represent the findings.
6. Producing the report: The themes were summarized and reported here in the RESULTS AND DISCUSSION section.

Generally, the use of reflexive thematic analysis can provide valuable insights. However, a known limitation is that the results are not final and may change with the availability of new data (Braun and Clarke, 2023).

Hierarchical Task Analysis

A HTA was used to summarize ice navigation on a CCG icebreaker based on insights from the interview transcripts. HTA is a descriptive method used in human factors analysis to illustrate the components of human interaction with a system (Lee, et al., 2017; Stanton, et al., 2013). Variations of HTA have been commonly applied in the maritime domain including Sharma, et al. (2019), Berlin and Praetorius (2023), and Musharraf, et al. (2023).

The HTA was conducted following the guides of Lee, et al. (2017) and Stanton, et al. (2013). First, the purpose and goal of the task of ice navigation was defined and decomposed into sub-goals. For this analysis, the codes developed in the thematic analysis were used to identify the sub-goals. The goal and sub-goals were mapped to provide a visual representation of the task. Next, plans, outlining the order that subgoals are actioned, were added to the map.

The use of HTA provided a comprehensive description of the system that was used to identify areas of potential error and high cognitive demand (Lee, et al., 2017; Stanton, et al., 2013). The HTA provided only an initial overview of the system and further analysis will be needed to fully apply UCD to the development of technology beyond the conceptual stage.

RESULTS AND DISCUSSION

Thematic Analysis

The results of the thematic analysis produced three themes: priorities, learning from experience, and charting. The findings on each theme are summarized in Tables 2, 3, and 4 respectively. The tables include a quote to represent the theme followed by a list of the findings.

Priorities

For the theme of priorities, safety was the first priority when making decisions related to ice navigation on this vessel. This includes both the safety of their vessel and crew as well as the safety of the vessels and people they are supporting. The second priority for this vessel can be situation dependent but it is typically time. The importance of time depends on the operation.

In search and rescue, time is critical. Conversely, during non-critical nighttime operations the vessel will sometimes proceed slowly to reduce noise while the crew sleeps. A tertiary priority for this vessel is expense, including fuel usage. The vessel is providing a service for safety and is not profit driven. Several interviewees described something similar to ‘cost is not a priority when it comes to saving human life’. Fuel usage is considered, but is often an aspect of monitoring rather than a direct component of moment-by-moment decision making. It is worth noticing that avoiding ice is not always a priority because this is a vessel designed for ice. Sometimes the vessel goes into ice intentionally for search and rescue or research operations.

On this vessel it is the crew who sets priorities. This means the crew themselves are making decisions. They do not need to have approval from management or a company to deviate from planned navigational routes. The crew are deciding what is the safer and more efficient routes while navigating. The crew noted that this was a difference between CCG operations and commercial operations.

Table 2. Findings on the theme of priorities

Priorities “Yes, time is important, but safety is most important.” (Tran and Veitch, 2024, p. 104)
Safety is the number one priority.
Time is a priority, but how important time is depends on the operation (e.g. time is critical in search and rescue but less important in non-emergencies).
Expense, including fuel usage, is a secondary priority. This vessel provides a service for safety and is not profit-driven. Expense is not a priority when it comes to saving human life.
Avoiding ice is not always a priority. This vessel is designed for ice; sometimes, it goes into ice for rescue or research.
The crew decides the route and can deviate from the route as they see fit. The crew themselves make decisions that balance priorities.

The discussion of ice navigation decision making reflected a recognition primed decision model. The recognition primed decision model is a naturalistic decision-making model which aims to describe how experienced professionals make quick decisions often in safety critical situations (Klein, 2008). The recognition primed decision model describes the decision-making process as mental simulations that are informed by knowledge gained from past experiences. Mental simulations are used to generate possible outcomes of decisions resulting in a decision that is “workable,” not necessarily “optimal” (Stone, et al., 2018). On this vessel, the crew is not directly weighing navigational decision options against each other, rather, performing mental simulations of what might happen, based on experience, if certain actions are taken.

Learning from Experience

For the theme of experience and training, ice navigation was not covered in the crew’s cadet training. There are specialized short form ice navigation courses (e.g., basic and advanced Polar Code courses) that can be taken as additional training. These courses are required for masters, chief mates, and navigation offers to operate in polar waters (International Maritime Organization, 2016). However, ice navigation is primarily learned from experience. It takes many years of practice to be skilled in ice navigation.

The crew emphasized the value of the captain’s knowledge. The captain holds specific knowledge that is passed down to the crew over time. Some of this knowledge is specific to location, such as the captain’s knowledge of where ice pressure will build up in a particular bay with a particular wind direction. As is reflected in the quote in Table 2, some of the crew did not feel they had the experience needed to perform ice navigation operations as effectively as the captain.

Table 3. Findings on the theme of learning from experience

Learning from Experience “I just don't have the feel for the vessel like he [the captain] does. He knows how to use the sticks to turn the vessel in the ice. Like even the other day I was backing up in the track, he let me do it in St. Barbe. I had a lot of difficulty keeping it straight, backing up in the ice. So in theory I could, but it would take a lot of practice to get right.” (Tran and Veitch, 2024, p. 100)
Ice navigation is not covered in cadet training. Polar courses can be taken after graduation, but ice navigation is primarily learned from experience.
It takes many years of practice to be skilled in ice navigation.
The captain holds knowledge that is passed down to the crew over time. Some of this is specific to a location, such as where ice pressure builds up in a particular bay with a specific wind direction.

The analysis of the learning from experience theme reflects the differences between observational and physical practice. In the current system, ice navigation is primarily learned through observational practice. The crew gets some physical practice using the vessel controls, but likely not at a rate that enables them to learn the necessary skills. The targeted combination of physical practice along with observational practice has been shown to be an effective method of learning (Wulf, et al., 2010). Adding targeted physical practice related to ice navigation may reduce the time needed to learn navigational skills, such as ship handling in ice.

Charting

For the theme of charting, the crew of this vessel charts their planned routes twice, once on paper charts and once on ECDIS. In some of the areas this vessel operates, electronic charts are not of sufficient quality. The crew relies on paper charts for these areas. For example, the area of interest may be a small section of a large electronic chart that does not have the detail needed for the types of operations being performed.

On this vessel’s ECDIS, information such weather and ice charts cannot be overlayed directly on the electronic chart. This means when plotting a route, a navigator has to look at several different charts and sources of information, remember where this information is relevant, and then use this information to decide on waypoint locations in ECDIS.

The theme of charting relates to pursuit and compensatory tracking displays. Stone, et al. (2018) provides an overview of the two types of displays. In a pursuit tracking display the system and the error from the desired state is indicated on a single display. For example, road lines are a pursuit display because the driver can see when a road line is crossed (the error state) or if they are within the road lines (the desired state). In a compensatory tracking display only the error state is shown. For example, a speedometer is compensatory display

Table 4. Findings on the theme of charting

Charting “If there was like some sort of program like on where I could accurately superimpose waypoints on a satellite image, you know? Yeah. Or an ice chart, same way, right. If I can accurately do that.” (Tran and Veitch, 2024, p. 83)
Charting is done twice on ECDIS and on paper charts. These charts are separate.
Electronic charts for many areas of operation are of insufficient quality (e.g. a small area of a big chart). Paper charts are used in these instances.
Ice charts, weather information, tides and currents, shear lines from satellite imagery, etc., cannot be overlayed on this vessel’s ECDIS.

because a speed exceeding the limit (the error state) is shown but the speed limit (the desired state) is not. The current ECDIS system resembles a compensatory tracking display because it shows the planed route (a potential error state) but not the information which influenced the route (the desired state). Pursuit tracking displays usually result in better performance with fewer errors compared to compensatory tracking displays (Stone, et al., 2018).

Hierarchical Task Analysis

The results of the HTA for ice navigation on this vessel are shown in Figure 1. Much of the information in the HTA results reflects what is known from existing sources, such as Snider (2012). However, the HTA provide some interesting findings specific to this vessel.

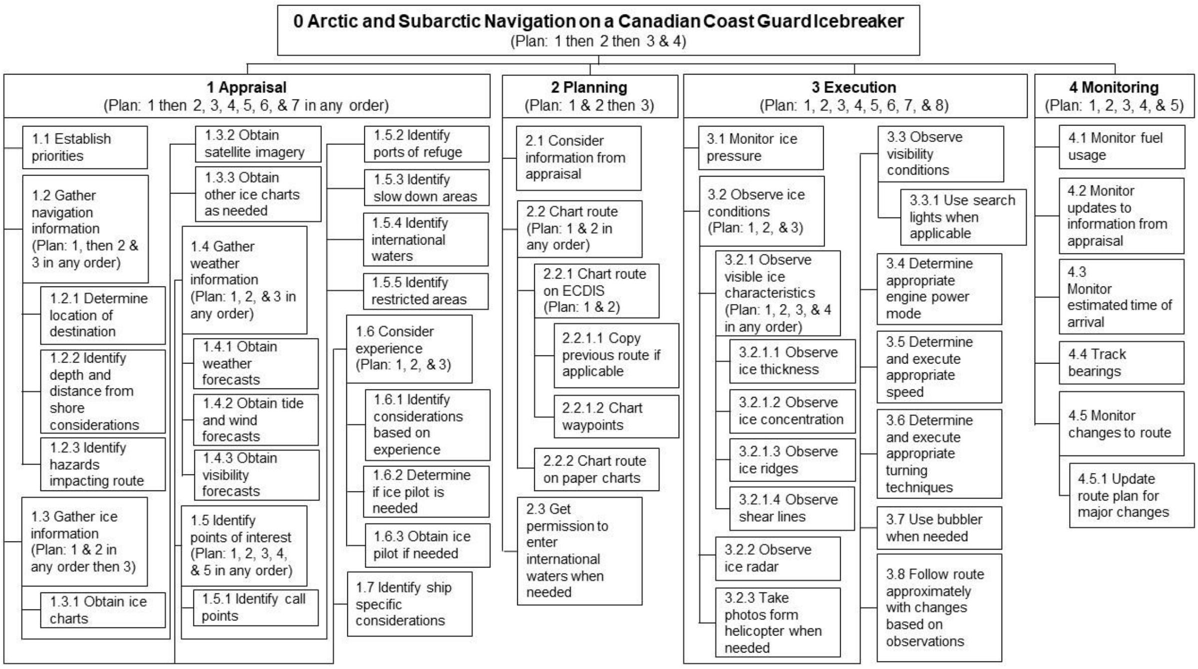

Figure 1. Hierarchical task analysis for ice navigation on a CCG icebreaker

The overall goal of the system is Arctic and Subarctic navigation on this vessel. This goal is broken down into four sub-goals: appraisal, planning, execution, and monitoring. The appraisal sub-goal is conducted first, then the planning sub-goal, followed by the execution and monitoring sub-goals concurrently. In the appraisal sub-goal, priorities are established and then information is gathered. The information gathered includes navigational information such as location of destination and hazards, ice information such as ice charts and satellite imagery, weather information such as tide and wind forecasts, and points of interest such as ports of refuge and international waters. Other considerations include experience such as things specific to the area known from experience and ship specific information such as ice class and capabilities.

In the planning sub-goal, a route is charted considering all of the information gathered during the appraisal sub-goal. The route is charted twice; once in ECDIS and once on paper charts. In ECDIS, specific waypoints are charted and routes may be carried over from previous voyages. If international waters are in the planned route, such as going near Greenland, permission must be granted before entering the waters.

In the execution sub-goal, the approximate route from the planning sub-goal is followed. While following the route, the ice pressure and conditions are monitored visually from the bridge and deck, on the ice radar, and with a helicopter if needed. Maneuvering considerations are implemented, such as engine power mode, use of the bubbler, identifying and maintaining an appropriate speed, and using appropriate turning techniques. The route followed is not necessarily the exact route charted in the planning sub-goal because changes are made based on observations and monitoring.

In the monitoring sub-goal, changes to the route, fuel usage, and updates to sources of information are tracked. For major changes, the route plan is updated, but for minor changes, the route plan itself is not updated.

System Strengths and Limitations

The results of the thematic analysis and HTA helped identify strengths and limitations of ice navigation on this vessel. A strength of the system is that it is adaptable. The crew is able to change the process of route planning, or the decision to follow the route, based on the information available to them and changes their priorities. Additionally, the tasks and the responsibilities for tasks are well defined. The crew knows who is doing what and who is responsible for what. Furthermore, the crew understands the accuracy of the information being used in route planning. Sometimes, additional sources of information are needed or the information quality is low because of environmental conditions. For example, satellite imagery is less clear when it is cloudy. The crew understands these limitations and how that impacts their decision making.

A limitation of the system is that the quality of decision making is dependent on expert knowledge and experience. If a new captain replaces the existing captain, they may not hold the area-specific knowledge that is used in decision making. Another limitation is that the consequences for error can be severe. An error in decision making could result in damage to the vessel or the vessel becoming stuck in ice. As this is the support vessel for the area, it would take a long time for additional support to reach the area if an error did occur. Furthermore, information is gathered from many different sources and the integration of this information into a route plan may be demanding on the working memory. Additionally, all route planning is done twice. Duplicating the task leaves the possibility for errors in one chart that are not in another chart and miscommunication about the planned route.

Areas for Future Support

Five areas for further support to ice navigation and route planning on this vessel were identified.

1. Combine simulator practice with the existing observational practice for learning physical control skills.

The analysis identified a need for additional physical practice of ship handling in ice. Currently, ice navigation is primarily learned through observation. The addition of physical practice could reduce the time needed to learn skills for ice navigation so that additional crew are able to perform necessary operations. Considering the safety risk of inexperienced navigators gaining physical practice with the controls of an actual vessel, bridge simulators with realistic controls could provide a lower-risk environment for physical practice.

2. Improve the quality of electronic charts for remote areas at least to the standard of paper charts.

Insufficient quality of electronic charts for remote areas could pose a safety concern for vessels operating in these areas. Improving the quality of electronic charts is needed in order for electronic charting systems to become standard use in these areas. Developers of decision support and low-level automation technologies that utilize these charts also need to consider how insufficient chart quality may impact the technologies' ability to support ice navigation and the overall impact on the system users.

3. Develop a template or application to print electronic charts as a replacement for planning routes separately on paper charts.

Creating two charts for a route plan could increase the likelihood of error and miscommunication and increase the cognitive demands of ice navigation. A system that allows printing of electronic routes as paper charts instead of hand drawing the route on charts could eliminate the need for duplicate charting.

4. Update to an ECDIS that can use overlays and train crew to use ECDIS overlays in the existing system.

The addition of ECDIS overlays could reduce the working memory load and reduce the likelihood of error while planning a route. It could also help the crew understand why a route was plotted a certain way when making decisions during route execution. Overlays of weather information are possible in other systems. A human factors analysis of these overlays is outside of the scope of this research but should be completed before overlays are introduced on this vessel. If the use of ECDIS overlays is introduced for this vessel, the crew should also be trained to use ECDIS overlays so that the system can be better utilized and can support rather than frustrate the users.

5. Develop an ice chart and satellite imagery overlay for ECDIS.

Ice charts include information about specific information that impacts route planning on a chart separate to where the route in drawn. Having this information in multiple displays means the information is held in the working memory while route planning and may increase the likelihood of errors. A way to reduce the number of information displays and demands on working memory may be to overlay the ice chart information in ECDIS itself.

Limitations

This analysis is of interviews at one point in time with the crew of a single vessel. Therefore, the results do not reflect a broad understanding of ice navigation concerning different vessels, locations, operations, or bridge technologies. Future research could expand on this work by investigating ice navigation decision-making with a larger scope.

CONCLUSIONS

Ice navigation decision making is a complex task that can have significant consequences for error. It is essential that technologies developed to support ice navigation focus on user needs to reduce task complexity. This analysis identified several areas where future technologies can better support ice navigation on this CCG vessel. For example, the development of technologies for simulator training could enable physical practice to reduce the time needed to learn navigational skills. Improvements to electronic charts and charting tools could eliminate the need for duplicate charting. Development of overlays and tools for existing navigational systems, such as ECDIS, could improve the quality of information displayed thereby reducing errors in communication and decision making. In conclusion, the findings of this research can be used as a starting point for the user-centered design of technologies that better support seafarers in ice navigation decision-making.

ACKNOWLEDGEMENTS

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC).

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