Ecological Interface Design in Neuro-Critical Care

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Neuro-critical care is a data-intensive environment that requires physicians to integrate information across multiple screens, sources, and software. Despite the advances in neuromonitoring techniques, interfaces that allow for viewing and analyzing of historic data are not common. However, historical data is critical to identify patterns important for patient care. Instead, physicians view the trends of a patient's neurophysiological variables by continuously watching the bedside monitor or they rely on checking the paper (or digital) charts for a patient where variables have been recorded periodically (usually once an hour). In neuro-critical care, physicians need to understand the historic and current state as well as predict the future state of intracranial pressure (ICP). ICP is the most monitored brain-specific physiologic variable in the Intensive Care Unit (ICU) and is considered a biomarker for secondary brain injury. As a result, ICP would benefit greatly from showing key patterns important to patient state and care.

The ICU is a stressful, dynamic, and time-sensitive environment where the performance of physicians and their ability to correctly diagnose and manage patient treatment has a significant impact on patient outcomes. Physicians rely on the bedside physiologic monitor to detect changes in physiologic variables. The monitor must provide the information required to understand the patient's condition so physicians can determine the optimal treatment plan. With the high cognitive demands and complex sociotechnical environment of the ICU, an opportunity exists for improved neuro-critical care monitoring to support physicians' decision-making. Ecological Interface Design (EID) is an approach to interface design that has proven effective for complex, sociotechnical, real-time, and dynamic systems. Research suggests that an EID approach combined with user-centered design has a positive impact on performance, especially in unfamiliar scenarios.

The objective of this research is to explore an EID design approach combined with user-centered design to enhance the bedside physiologic monitor through the addition of visualizations that help support physicians' understanding of complex relationships and concepts in neuro-critical care. The hope is that providing more-advanced visualizations on the bedside physiologic monitor will lead to improved situation awareness, decreased mental workload, and expertise development acceleration of novice clinicians in the neuro-ICU.

The work presented in this thesis builds on the Cognitive Work Analysis (CWA) and observations in the ICU already completed by Uereten et al (2020). The design of the visualizations for use on the bedside physiologic monitor was highly iterative and involved the inputs from the CWA and observations as well as ongoing feedback and focus areas provided by Dr. Victoria McCredie, our clinical collaborator and critical care physician at Toronto Western Hospital. The visualizations were evaluated and validated in semi-structured interviews with trainees (fellows) and experts (staff physicians) in neuro-critical care. The semi-structured interviews with trainees were used as a preliminary usability assessment of the visualizations and the interviews with staff physicians were used to iterate and refine the designs. The results from both sets of interviews were used to create a final design prototype that is currently being tested in a usability study with trainee physicians (January-March 2023).

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

ICU	Intensive care unit
EID	Ecological interface design
ICP	Intracranial pressure
CSF	Cerebral spinal fluid
CPP	Cerebral perfusion pressure
EVD	Extra ventricular drain
TBI	Traumatic brain injury
EMR	Electronic medical record
PRx	Pressure reactivity indices
MAP	Mean arterial pressure
SRK	Skills, rules, and knowledge
CWA	Cognitive work analysis
AH	Abstraction hierarchy
SBB	Skill-based behaviour
RBB	Rules-based behaviour
KBB	Knowledge-based behaviour
SA	Situation awareness
GOS	Glasgow outcome scale

Chapter 1
Introduction

Each year there are approximately 4 million patients admitted to the Intensive Care Unit (ICU) in the U.S. with an average mortality rate ranging from 8-19% (Philip R Lee Institute for Health Policy Studies, 2021). In the hospital, medical errors are most likely to occur in the ICU due to the complexity of care. Admitted patients in the ICU receive on average 1.7 medical errors a day, some of which are life-threatening (Camire et al., 2009). It takes years to develop expertise in any environment and this is compounded when the environment is complex.

The ICU is a complex sociotechnical environment in which patients require constant monitoring and frequent intervention. This environment results in cognitive strain on the healthcare workers, thereby impacting their decision-making and ultimately causing deteriorated care quality and patient safety (Faiola, 2015). Neuro-critical care is the area of critical care that focuses on patients with brain trauma. Despite advances in information management and clinical informatics, data collection in the ICU is dominated by single-sensor single-indicator displays (Andrade et al., 2020). This means that for each device, only a single variable is recorded. Clinicians are required to parse through multiple sources including monitors, screens, and even paper sources to understand a patient's condition (De Georgia et al., 2015). This makes retrieval of patient data challenging and causes a higher cognitive workload (Norris et al., 1997). In addition, inadequate storage on the monitoring devices prevents lookbacks at historic data or trend tracking. For neuro-critical care applications, physiologic data trends are essential in understanding the original state of the patient and the current outlook to prevent secondary brain injury (McCredie, 2019). Companies have recently begun to design new software tools which aggregate and display data in the ICU into one integrated display; however, this has yet to be applied in the neuro-critical domain.

Ecological Interface Design (EID) is an approach to interface design that was first introduced for complex sociotechnical, real-time, and dynamic systems. EID has been used in multiple applications including aviation displays, power plants, and healthcare monitoring (Momtahan & Burns, 2004). EID reduces cognitive load by making constraints and complex relationships easily visible. The goal of EID is to stimulate skill-based behaviour which is the most automated and least conscious level of cognitive decision-making (Schewe & Vollrath, 2020). This allows for cognitive resources to be used for higher-level, more involved problem-solving, especially in unanticipated situations (Vicente, 2002). Integrated interfaces, such as ecological interfaces, display data in a more integrated design into higher-level information task requirements (Rasmussen, 1999). Ecological interfaces often display multiple graphics that help depict relationships between variables.

The high cognitive pressures of neuro-critical care demand an improved monitoring interface to aid in the decision-making process for clinicians in unexpected scenarios. An interface that assists a clinician's understanding of complex relationships will allow novice clinicians to develop expertise more quickly.

1.1 Objective of Research

This research aims to investigate how neuro-critical displays can present information to better support physicians' decision-making and situational awareness. This research is built upon the results of cognitive work analysis and abstraction hierarchy previously completed. There are several objectives of the research outlined below:

1) Development of EID visualization display for use in neuro-critical care.

2) Preliminary usability assessment of EID visualizations by novices in neuro-critical care through semi-structured interviews.

3) Feedback on EID visualizations from subject matter experts in neuro-critical care through semi-structured interviews.

4) EID design compilation and implementation of feedback to generate a final prototype for use in a usability study to assess the performance of the redesigned interface.

The results of this work are currently being used in a usability study with trainee physicians in neuro-critical care (January-March 2023) to understand if the standard interface with EID enhancements can assist trainees' situational awareness, performance, and expertise development to increase treatment quality. This study hypothesizes that resident physicians in a neuro-critical care setting will have improved performance when completing tasks with a redesigned interface with EID visualizations than the conventional visualization dashboard.

1.1.1 Research Process Overview

The process followed was like that of a user-centered design process in which there was analysis, design iteration, and design evaluation. Before this work, an in-depth analysis was undertaken including a cognitive work analysis which is a systems approach to analyzing complex systems. The results of this cognitive work analysis led to some key design requirements discussed further in Chapter 3. The results of the cognitive work analysis combined with consultation and collaboration with a subject matter expert led to the creation of static designs which were tested in a preliminary usability assessment with novice physicians and validated through feedback elicitation interviews with expert physicians. The results of the preliminary usability assessment and the feedback elicitation sessions were used to modify the design and create a final prototype. This final prototype will be used in a usability study (January-March 2023) to compare how the redesigned interface can help with an understanding of key neurophysiologic concepts and increase the situational awareness of novice physicians.

1.2 Structure of Thesis

This thesis is organized into 7 chapters described below. The structure of this thesis aims to document the design process of developing an EID interface for use in a future usability study.

Chapter 1: Introduction

This chapter introduces the topic, and objectives, and describes the motivations for the research.

Chapter 2: Background

This chapter serves as a literature review of current displays in neuro-critical care, neurophysiology background, and the application of EID for complex sociotechnical environments.

Chapter 3: Ecological Interface Design in Neuro-critical Care

This chapter outlines the results of the cognitive work analysis and the design process for the EID visualizations. At the end of the chapter, the preliminary designs are presented along with a description of each design.

Chapter 4: Preliminary Usability Assessment (Novices)

This chapter outlines the results and implications of the preliminary usability assessment and feedback from semi-structured interviews with novice clinicians.

Chapter 5: Design Refinement and Feedback Elicitation (Experts)

This chapter presents and discusses the results of semi-structured interviews with experts in neuro-critical care. These interviews were used to gather feedback from the preliminary EID visualizations and refine the preliminary designs.

Chapter 6: Final design

Chapter 6 describes how the visualizations were combined into a final display prototype and the usability considerations that impacted the final design.

Chapter 7: Conclusions and Future Considerations

Chapter 7 discusses the implications of the work, strengths and limitations, and future considerations.

Chapter 2
Background

2.1 Neuro-critical Care Background

In Canada, approximately 165,000 people suffer from an acute brain injury each year and stoke, and traumatic brain injury is the leading cause of death and disability worldwide (Centers for Disease Control and Prevention, 2015). The goal of neuro-critical care is to anticipate, prevent and treat secondary brain insults, which may be described as the changes that evolve in the brain after a primary brain injury (Hadded & Arabi, 2012). For traumatic brain injury patients, in the first 48 hours, 40% of patients show a clinically relevant neurological worsening and the most powerful predictor of this was elevated intracranial pressure or ICP (Juul et al., 2000). A common phrase in neuro-critical care is “time is brain” which emphasizes that the time from the first symptom to treatment is one of the largest determinants on long-term health outcomes and for that reason, physicians need to be able to identify neurological worsening quickly and act on treatment accordingly (Saver, 2006). Delays in clinical decision-making have the potential to result in severe consequences for patient outcomes.

The ICU is a stressful, dynamic, and uncertain environment. All these characteristics pose additional challenges to decision-making (Power et al., 2018). In the ICU, critical care physicians are required to make accurate decisions promptly and the consequences of incorrect diagnoses or treatment plans can result in severe consequences. Consequences can be a result of errors of commission including wrong diagnosis or incorrect therapy or omission, where a physician may not fully appreciate the extent of a patient’s condition or deterioration (Lighthall & Vazquex-Guillamet, 2015). Physicians rely on bedside physiologic monitors to detect changes and abnormalities in vital signs. It is of utmost importance that the bedside physiologic monitor supports physicians' understanding of the patient’s condition and outlook so they may determine the best treatment plan for a patient.

To better understand the physiologic variables that are important in neuro-critical care, Section 2.2 presents background information on neurophysiology.

2.2 Neuro-Physiology Background

Cerebral pathophysiology is governed by two key principles namely the Monroe-Kellie doctrine and cerebral autoregulation. The Monroe-Kellie doctrine states that the sum of the intracranial volumes of blood, brain parenchyma, and cerebrospinal fluid (CSF) are all constant and that an increase in one of these volumes must be offset by an equal decrease in another, otherwise, the pressure will increase (Rangel-Castillo et al., 2008). In the brain, the two main buffers are CSF and venous volume. This means that these two components have the greatest ability to adapt to accommodate an increase in the volume of intracranial contents. However, once these volumes adapt to a lower state-or in other words the compensatory reserve is exhausted- further volume increases lead to a pressure increase in the intracranial compartment. This pressure is referred to as intracranial pressure or ICP. ICP is key to predicting and preventing traumatic brain injury. In neuro-critical care, the healthcare team must understand ICP to provide the best care and assess therapeutic measures. Cerebral autoregulation is the physiological process of the diameter of cerebral blood vessels changing to maintain constant blood flow to the brain. This autoregulatory mechanism explains why large changes in systolic blood flow produce small changes in cerebral blood flow. The pressure autoregulation mechanism prevents "*cerebral ischemia due to hypotension and against excessive flow during hypertension, when capillary damage, edema, diffuse hemorrhage, and intracranial hypertension might otherwise result*" (Rangel-Castilla et al., 2008). Patients with traumatic brain injury often experience an absence of impairment in pressure regulation which can lead to an increased risk of secondary injury (Rangel-Castilla et al., 2008). When autoregulation mechanisms are intact, a decrease in cerebral perfusion pressure (CPP) results in the dilation of blood vessels which thereby causes an increase in ICP due to the decrease in compliance because of cerebrovascular volume increase. Patients who have impaired autoregulation are associated with worse outcomes (Rivera-Lara et al., 2017).

2.2.1 ICP Monitoring

ICP elevation contributes to death and long-term disability and ICP monitoring has proven to be valuable for providing care for neuro patients including acute care of Traumatic Brain Injury (TBI), hydrocephalus, subarachnoid hemorrhage, cryptococcal meningitis, and brain tumors (Kawoos et al., 2015). Two of the most common ways to measure ICP are through an extra ventricular drain (EVD) and microtransducer ICP monitors (Nag et al., 2019).

ICP measurement with an EVD involves placing a catheter into one of the ventricles of the brain. One of the benefits of ICP monitoring with an EVD is that the EVD can also be used to drain CSF to relieve pressure and administer medicine intrathecally (Nag et al., 2019). Placement of the EVD requires surgery and this surgery has been associated with postoperative hemorrhage. In addition, placement of the EVD can be challenging for younger patients with smaller ventricles (Nag et al., 2019). For EVD monitoring, the ICP signal can only transduce when the drain is closed. Therefore, continuous monitoring of ICP is not possible with this method.

Microtransducer ICP monitors include fiber optic devices, strain gauge devices, and pneumatic sensors. This monitoring technique allows measurement through the intraventricular, intraparenchymal, epidural, subdural, or subarachoindal compartment. However, the most widely used microtransducers measure ICP intraparenchymally. Surgery is required to place the microtransducer intraparenchymally but compared to EVD placement, the procedure is less invasive with a lower risk of complications (Nag et al., 2019). A common disadvantage of microtransducers is that they are more expensive than EVDs and they cannot be recalibrated once placed, which can impact the precision of the ICP measurements (Nag et al., 2019).

2.3 Current Displays in Neuro-critical Care

The monitoring displays in hospitals largely depend on the center. Multimodal monitoring with trending abilities is becoming more common but many centers still track information on paper flowsheets (De Georgia, 2015). It is common for large volumes of data to be collected from disparate sources which require physicians to sift through multiple screens, paper charts, and different software to fully understand the history and current state of the patient. Although real-time data on the bedside physiologic monitor is available, it is challenging to understand trends with simple displays. Advancements in electronic medical records (EMR) have helped with this however, many of the EMRs display data in a format reminiscent of the typical paper ICU chart in tabular format (De Georgia, 2015).

For neuro-critical care, there are two main categories of displays. Standard displays include real-time monitoring and waveform information for vital signs. Advanced displays include multi-modal monitoring that allows for trending and more advanced visualizations of data.

2.3.1 Real-time Bedside Monitoring

The Philips Intellivue is a common bedside patient monitoring device that displays physiological waveform data including ECG, blood pressure, ICP, heart rate, and others. It also provides numeric values for these vital signs and upper and lower alarm limits. When a patient has an ICP monitor, this sensor can be connected to the monitor and the waveform information can be displayed (Sun et al., 2020).

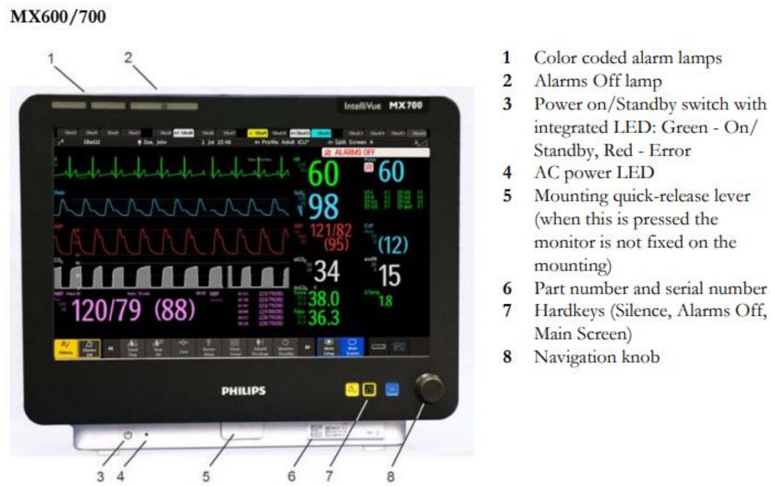


Figure 1: Philips Intellivue Monitor (Philips, 2013)

In the ICU, the nurses and physicians use real-time bedside physiologic monitoring to understand changes in vital signs. With only the real-time monitor, physicians rely on the nurse to chart the value of physiologic variables typically once an hour. There is inconsistency with how this number is reported (i.e. maximum, average, or range) and the flowsheet can be challenging to understand the trends as it is typically in a tabular format.

2.3.2 Graphical and Integrated Displays

Graphical and integrated displays take information from the real-time bedside monitor and display it on a separate interface with more advanced visualizations (Drews & Westenskow, 2006). Several integrated displays exist in neuro-critical care and some examples include ICM+ multimodal monitoring and Moberg solutions.

The ICM+ software has been used for over 30 years in brain monitoring and collects data from a variety of bedside monitors. The data is displayed in various ways on the multimodal monitor screen including trend charts, histograms, and correlation of variables. The software has provided value both clinically and academically to understand relationships between physiologic variables in neuro-critical care (Smielewski et al., 2008). In the ICM+ monitor, pressure reactivity indices (PRx) provide information about whether cerebral autoregulation is intact and has helped determine the optimal CPP for patients. This variable is a moving correlation coefficient between mean arterial pressure (MAP) and ICP. This is an example of a calculated index that can help physicians make better decisions for patient diagnosis and treatment (Steiner et al., 2002).

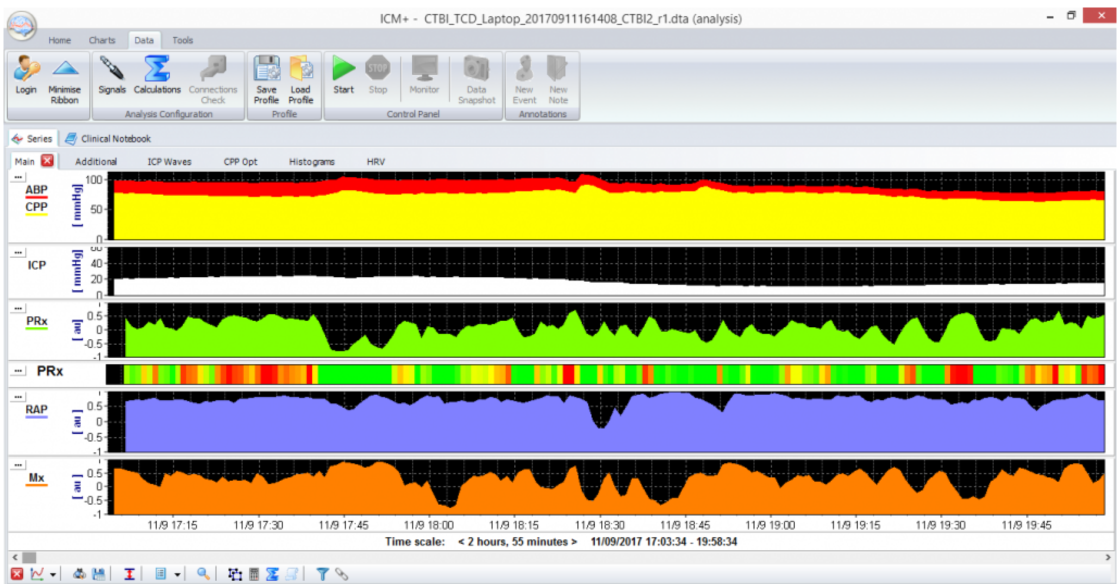


Figure 2: ICM+ Interface (University of Cambridge, 2017)

The CNS Monitor by Moberg solutions allows data streams from different physiological monitors to be displayed on one screen that allows bedside review of physiological trends by physicians, nurses, and other practitioners (Sinha et al., 2017). The visualization of multiple time series data for different physiologic parameters helps identify changes in variables and the relationship between variables. A visual of the CNS monitor can be seen below in Figure 3.

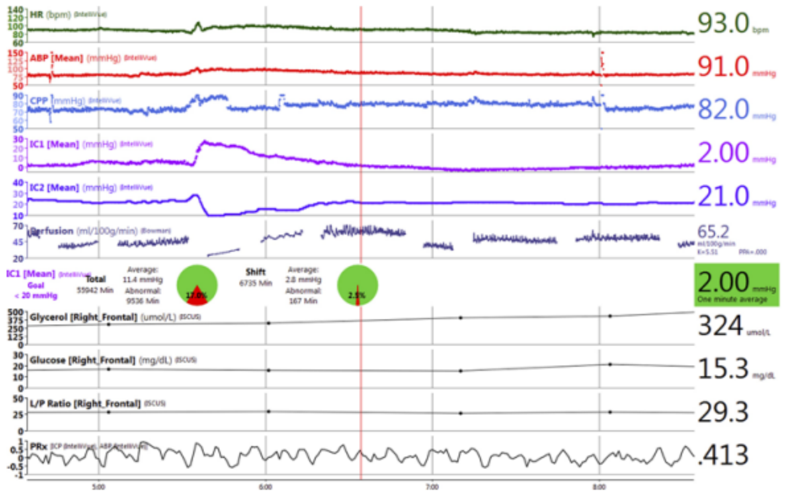


Figure 3: CNS Monitor, Moberg Solutions (Sinha et al., 2017)

The CNS monitor shows a 6-hour trend for various parameters including arterial blood flood, ICP, heart rate, and CPP. Moberg solutions also present two pie charts that represent the ICP burden as the percentage of the time that ICP stays above 20mmHg as a red wedge. The right pie chart shows the current time window, and the left pie chart shows the entire recording.

2.4 Ecological Interface Design

The complexity of neuro-critical care suggests that an EID approach to the monitoring interface would be able to improve the clinician’s knowledge of the system and situational awareness, thereby increasing performance and reducing errors. Ecological design is particularly useful in unfamiliar situations because it helps the users visualize the constraints and relationships within the complex system (Vicente, 1991). The principles of EID are based on two key frameworks in cognitive engineering research: the Skills, Rules, and Knowledge (SRK) taxonomy, and cognitive work analysis (CWA) including the abstraction hierarchy (AH).

2.4.1 Skills, Rules, and Knowledge Framework

The SRK model is a framework that categorizes human behaviour based on what cognitive level the activities and tasks are performed. This framework was developed by Rasmussen (1983) and is used to help interface designers determine how information should be displayed by taking advantage of human perception.

The three performance levels are skill-based behaviour, rules-based behaviour, and knowledge-based behaviour (Rasmussen, 1983).

1. **Skill-based behaviour (SBB):** This is routine behaviour and requires little conscious effort from the user. SBB is the most automated form of behaviour and requires little cognitive resources to complete.

2. **Rule-based behaviour (RBB):** This level of behaviour involves following a written or remembered rule or procedure. Like SBB, RBB is still familiar to the user but may require an added level of cognitive effort to execute the action. Rules can be written instructions or derived from previous experience. An understanding of the underlying principles of the system is not required to execute rule-based behaviour.

3. **Knowledge-based behaviour (KBB):** KBB kicks in when the task completed is unanticipated or unfamiliar. KBB initiates when the task being completed has never been completed. This behaviour requires the highest level of cognitive control and requires the user to understand the constraints and laws that govern the system.

Cognitive load is greatest in KBB and least in SBB. The goal of EID is to elicit skill and rule-based behaviour to allow for more cognitive resources to be dedicated to KBB, which is required for higher-level problem-solving in unanticipated situations (Rasmussen, 1983). In the design of an interface, KBB is supported by clearly displaying the relationships and constraints of the system to help users become better problem solvers (Vicente, 1991). The designer must have a thorough understanding of the work domain, and this is accomplished through the first stage of the ecological interface design method, CWA.

2.4.2 Cognitive Work Analysis

An ecological display is the end-product of CWA. CWA is used to analyze complex sociotechnical work domains and identify the constraints imposed by the system, tasks, strategies, user competencies, and socio-organizational factors (Vicente, 1999). To perform the CWA, Rasmussen (1983) has proposed the use of an AH. The AH is a tool that is used during the work domain analysis of the CWA. It has five levels of abstraction that describe the work domain (Figure 4). Moving down, the AH levels answer how the components in the system are achieved, and moving up answers why the components of the system are present.

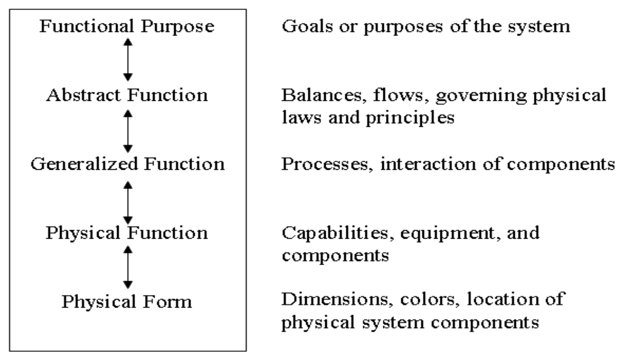


Figure 4: Levels of Abstraction (Hall et al., 2006)

As shown in Figure 4, the highest level of abstraction defines the goal of the system, and the lowest level of abstraction describes the physical components of the system. For EID, CWA and the AH help the designer understand the needs and display requirements of the system.

2.5 Ecological Interface Design Applications

The EID framework has been applied to multiple different domains including aviation, process control, military, and more recently healthcare. In the healthcare domain, EID has been used in hemodynamic monitoring, anesthesia monitoring, and neonatal intensive care monitoring and diagnosis (Momtahan & Burns, 2004). To date, EID has not been applied in neuro-critical care.

2.5.1 Ecological Interface Design for Novices

There is research to suggest that EID has a greater impact on the performance of novices than experts in the healthcare domain (Effken et al.,1997; Sharp & Helmicki, 1998).

Effken, Nam-Gyoon, & Shaw (1997) conducted a study to determine if an ecological interface design approach in hemodynamic monitoring can be used to improve the decision-making of nursing students. In this study, three different display types were compared: a traditional strip chart display (TSD), an integrated balloon display (IBD), and an etiological potentials display (EPD) (Effken et al., 1997). The participants were required to provide treatment to the "patients" based on the outputs of the displays. For each display, enhancements were made based on EID principles. Therefore, it was expected that performance would be highest for the EPD display type. The experiment compared the performance of novices (nursing students) and experts (graduate students). In the experiment, the ecological interface (IBD) allowed novices to achieve similar performance to that of the experts on the non-ecological interface (TSD). For both novices and experts, the EPD interface enhanced diagnosis and treatment performance. Expert performance was good for all displays, and for novices, performance increased significantly with the ecological design displays.

The results suggest that, for novices, simply displaying the process variables is not sufficient. Unlike novices, experts can detect complex variables and relationships for hemodynamic problems even when presented with a simple non-ecological display. However, the relationships between the variables are not as evident for novices, and therefore display enhancements are required.

In the neonatal ICU, research suggests that the use of an ecological display had a greater positive impact on the performance of residents (novices) than attending physicians (experts). In an experiment conducted by Sharp and Helmicki (1998), an EID display was compared to the conventional interface. The conventional interface displayed information in only alphanumeric format, whereas the EID display used graphical representations. The study analyzed three levels of expertise: residents, fellows, and attending physicians, and the participants were presented with a scenario and required to diagnose the clinical situation. The results of this study indicated that the EID interface led to higher performance. The results were significant for the residents however, the results were not significant for the group with the most experience (attending physicians). This could suggest that the attending physicians are more familiar and comfortable with the conventional display after many years of experience using it or that EID has the greatest benefit for novices.

Based on these research studies, it is evident that EID has a greater impact on the performance of novices than experts. One reason that experts do not see the same performance improvements may be that they have had years of training on the conventional interface. It is unclear whether with adequate training and exposure experts could have improved performance on an EID display.

2.5.2 Ecological Interface Design for Improved Situation Awareness

Situation awareness (SA) is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the future.” (Endsley, 1995). Endsley (1995) classifies SA into three levels: perception, comprehension, and projection.

1. **Perception:** Perception is characterized by an understanding of the status, attributes, and dynamics of parameters in the environment.

2. **Comprehension:** Comprehension goes a step beyond level 1 and includes an understanding of the significance of the parameters.

3. **Projection:** Projection is the ability to predict where the situation is going and interpret the changes in the future state of the system.

Higher situational awareness leads to better decision making and an interface that supports better situational awareness has an application in neuro-critical care. Research suggests that EID design can improve situational awareness over traditional interfaces (Burns et al., 2007).

In Burns et al (2007), a simulation study was conducted to determine if ecological displays could support improved situational awareness compared to conventional displays in an industrial setting. The experiment was conducted with participants from a boiling water reactor nuclear power plant (Burns et al., 2007). The participants were presented with 6 scenarios, 3 of which were categorized as “beyond-design basis” scenarios and 3 of which were categorized as “within-design basis” scenarios. The “beyond-design basis” scenarios were characterized by problems that are unfamiliar and therefore did not have a set procedure to follow. In contrast, the “within-design basis” scenarios were characterized by typical problems that the participants had encountered before and had set procedures to follow.

To evaluate the ecological display versus the conventional display, two situational awareness measures were employed using a process expert, and each participant was given a score. The first situational awareness measure was used to assess the participant’s understanding of the process variables. The interface was frozen, and the participants had to answer questions such as whether the process parameters have increased/decreased during the time of the scenario. This situational awareness measure assessed level 1 of situational awareness, perceiving. The second situational awareness measure was conducted by the experiment conductor freezing the screen and asking probing questions about the participant's understanding of the plant situation. The questions asked were focused on level 2 and level 3 situational awareness to assess the participant's understanding and prediction.

The results from the experiment indicated that the ecological display had the greatest impact on situational awareness in the "beyond-design basis" scenarios. All three levels of situational awareness were supported by the ecological interface for these scenarios. However, situational awareness for the "within-design basis" scenarios was not improved on the EID display. This suggests that EID does not support the operator's understanding of procedural tasks but in more complicated tasks, the benefits of EID can be realized.

2.5.3 Ecological Interface Design for Patient Monitoring

In a human factors review conducted by Andrade et al (2020), they investigated how advancements in patient monitors have impacted various performance measures in the ICU and operating room. The ecological interface design studies that were reviewed had varied results for performance. Some studies had no impact on performance (Jungk et al., 2000). However, others showed reduced identification time, time to initiate treatment, and treatment efficiency (Effken et al., 2008; Jungk et al., 2000; Effken et al., 1997). The authors of this review noted that integration of the user into the design process for advanced displays resulted in interfaces with higher usability (Andrade et al., 2020).

Jungk et al (2000) conducted two studies in the operating room with anesthesiologists. The first study was based on the principles of EID and the results indicated that there was no improvement from the baseline for the identification time of the physicians (Jungk et al., 2000). In the second study, a study was conducted that integrated feedback from users in the form of interviews and the results indicated an improvement from the baseline. This provides a compelling case for integrating EID with user-centered design.

Chapters 3 to 6 describe the process we followed to combine ecological interface design with user feedback for application in neuro-critical care.

Chapter 3
Ecological Interface Design for Neuro-critical Care

This chapter describes the results of the CWA and how these results were used to drive the design of EID visualizations for use on a bedside physiologic monitor in neuro-critical care. At the end of this chapter the results of the design process with feedback from critical care expert, Dr. McCredie, are described. The results of the design process include static visualizations that relate to the CWA and key neurophysiologic concepts. The resulting visualizations were then used in a preliminary usability assessment with fellows (Chapter 4) and design refinement and feedback elicitation with staff physicians (Chapter 5).

3.1 Work Domain Analysis in Neuro-critical care

A CWA was completed by Üreten et al (2020) in neuro-critical care. The results of the CWA can be described in the AH (Figure 6) on Page 20 (Üreten et al., 2022). To understand neuro-critical care data that physicians use for decision-making, an AH was built for two interconnected stakeholder domains. The first hierarchy described the domain of the patient and included the nervous system and cognition. The second hierarchy focused on neuro-critical care monitoring and treatment, and neuro-critical care challenges. This approach is similar to other AH models where the domain of the problem and the domain of mitigation are modeled together. The concepts and elements at the highest level of abstraction describe the purpose and goals of the system and the concepts and elements at the lowest level describe the physical components of the system. As described by the highest level of the AH, the purpose of neuro-critical care monitoring and treatment is to improve the patient's condition, facilitate long-term stability, and enable independent living (Üreten et al., 2020). Elements from the AH are described below.

For the patient:

- **Patient type:** Describes the type of patient such as adult, pediatric, or neonatal.
- **Patient condition:** Describes the condition of the patient such as obese, elderly, frail, or strong.

- **Damage:** Describes the type, amount, and location of the damage to a patient. This could include damage to the brain or other parts of the body.

- **Disease:** Describes the type and state of the disease the patient is experiencing. Some examples include subarachnoid hemorrhage, hydrocephalus, or ischemia.

For the neuro-critical care monitoring system:

- **Storage Capacity:** Describes the storage capacity of the monitoring system and interface. The storage capacity limits the ability of an interface to show historic trends.

- **Data Retrieval:** Describes the retrieval of patient information (including vital signs) for the past and current state.

- **Technology:** Describes the technology of the system including monitoring type, interface available, and screens.

At the interface of both systems

- **Signals:** This includes signals from the various sensors in the ICU including the frequency, amplitude, location that the signal is coming from, and the waveform. Signals indicate measurable physiological changes occurring in the patient.

3.2 Design Process

The design process of the visualizations was highly iterative and involved many stages (Figure 5). Throughout our subject matter expert was deeply engaged in providing feedback, and expertise on the challenges of neuro-critical care and contributed some design ideas.

The first challenge was to identify the best area of focus from the abstraction decomposition model. From the abstraction decomposition space, one key challenge emerged, that of understanding the patient's brain condition, specific to the patterns of ICP in the brain. These pressure patterns can show patient improvement, deterioration, or complex neurological situations. The following visualizations focus on this specific problem and look at ways to show ICP and the patterns that are critical for neuro-critical care monitoring. From the abstraction decomposition space, these visualizations focus on (AH: Nervous System, Physiology: Brain and Nervous System, condition and disease) and (AH: Neuro-critical care monitoring) specific to the monitoring of ICP and its indication of medication and treatment progress, secondary brain injury and the impact of physical intervention in the achievement of overall improvement of the patient condition.

There were four preliminary visualizations (version 1) designed that each related to different aspects of the abstraction hierarchy. These visualizations were iterated (version 2) to incorporate feedback from Dr. Victoria McCredie and to capture key neurophysiologic concepts. Figure 5 describes the process.

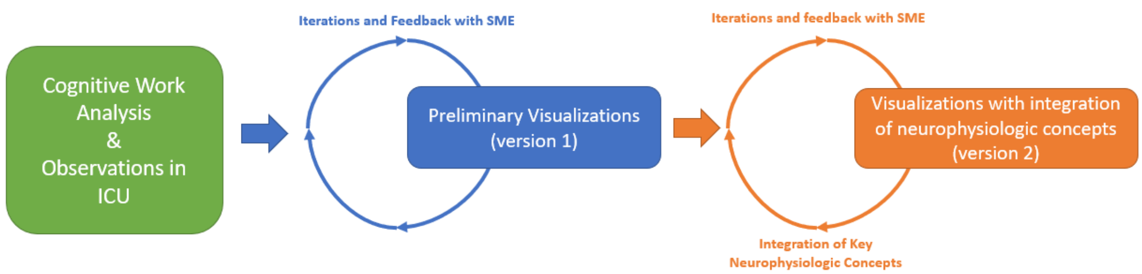


Figure 5: Illustration of the iterative design process that we followed to design the version 2 visualizations. There were four preliminary visualizations (version 1) that related to different elements of the AH. These visualizations were iterated with feedback from SME and integration of key neurophysiologic concepts.

In the following sections, I have described the evolution of the visual designs. An evaluation of the version 2 visualizations is later discussed in Chapter 4 and Chapter 5 with fellows and staff physicians respectively.

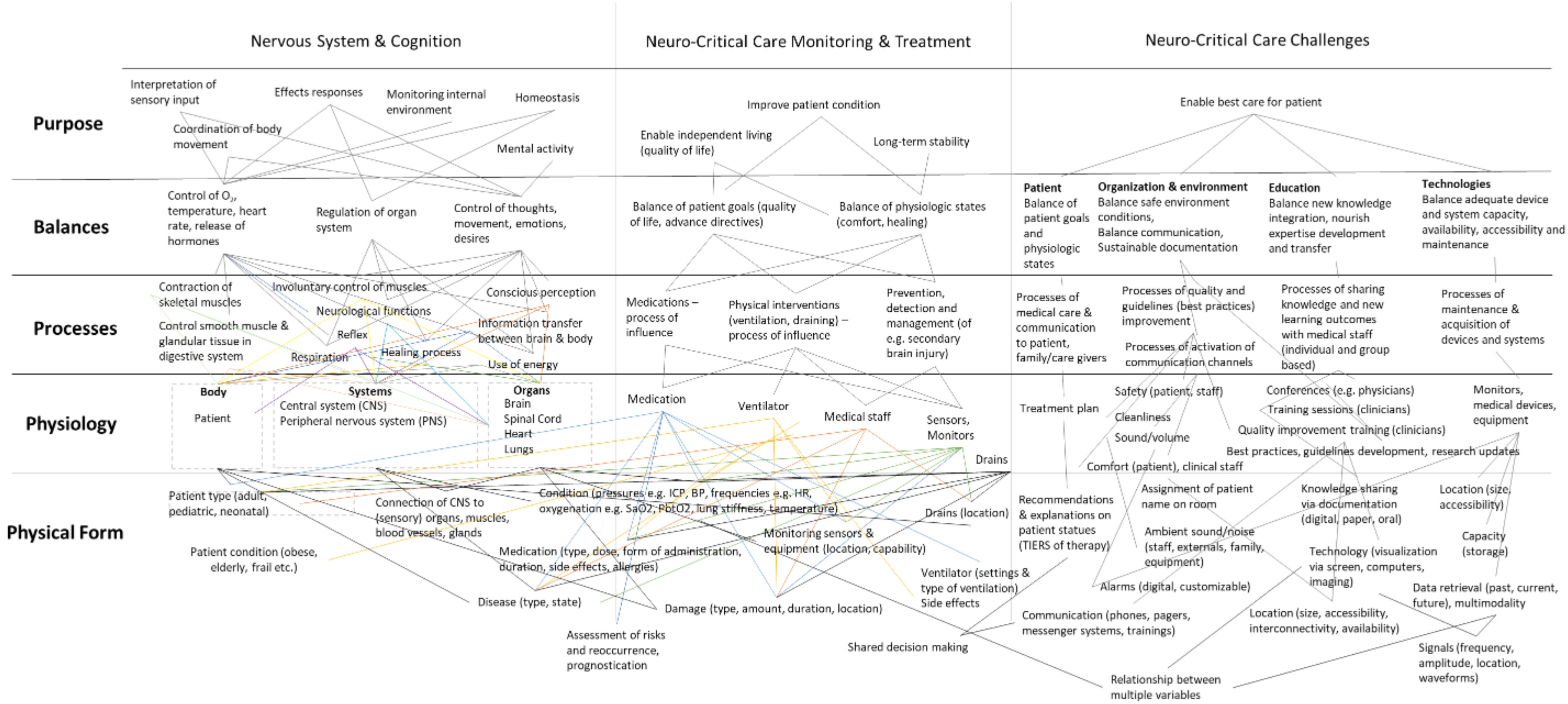


Figure 6: Abstraction Hierarchy for Nervous System and Cognition, Neuro-Critical Care Monitoring and Treatment, and Neuro-Critical care challenges (Üreten et al., 2022)

3.3 Preliminary Visualizations (Version 1)

The AH functions listed in Section 3.1 were used to design preliminary visualizations or version 1 visualizations. The preliminary visualizations are contributions from a co-op student in the Advanced Interface Design Lab (AIDL) at the University of Waterloo, Cathleen Grace Leone in collaboration with Ece Üreten. The preliminary visualizations aim to represent trends of ICP, visualize relationships that are important in neuro-critical care, and apply EID design principles. There are four preliminary visualizations that each relate to different elements of the AH: ICP waveform trend chart, connected waveform peaks to detect abnormal ICP, summation trend chart, and ICP dose histogram.

3.3.1 ICP Waveform Trend Chart

The first preliminary visualization, the ICP waveform trend chart, focuses on the ICP waveform peaks. The ICP waveform consists of three peaks. The first peak, P1, is the percussion wave which is a representation of arterial pressure. The second peak, P2 is the tidal wave and a proxy for intracranial compliance. The third peak, P3 is the dicrotic wave and a proxy for aortic valve closure. Under a normal intracranial physiological state, P1 should be the highest pressure, followed by P2, and then P3. When P2 is higher than P1, this suggested reduced intracranial compliance. Patients with poor compliance are at much greater risk, even if their ICP is at a normal level (Le Roux, 2016).

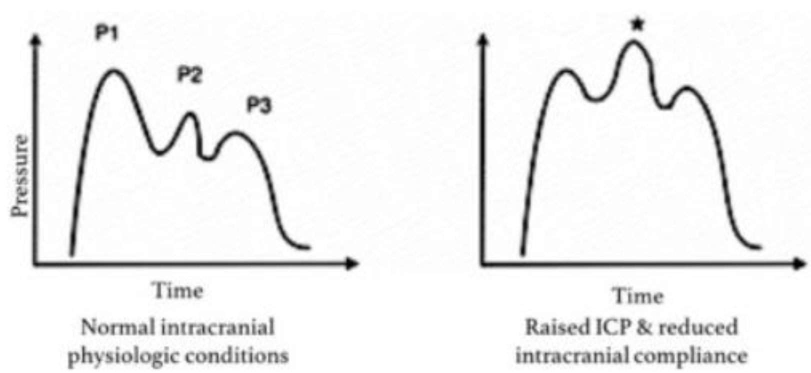


Figure 7: ICP waveform under normal and abnormal conditions (Harary et al., 2018)

The ICP waveform trend chart visualization depicted below in Figure 8 trends each peak of the ICP waveform and a data point is shown for each pulse cycle. The baseline represents the ICP of the patient between the pulse cycles. When P2 rises higher than P1, the trendlines cross and an alert shows up on the visualization as P2>P1 is an indicator of poor ICP stability.

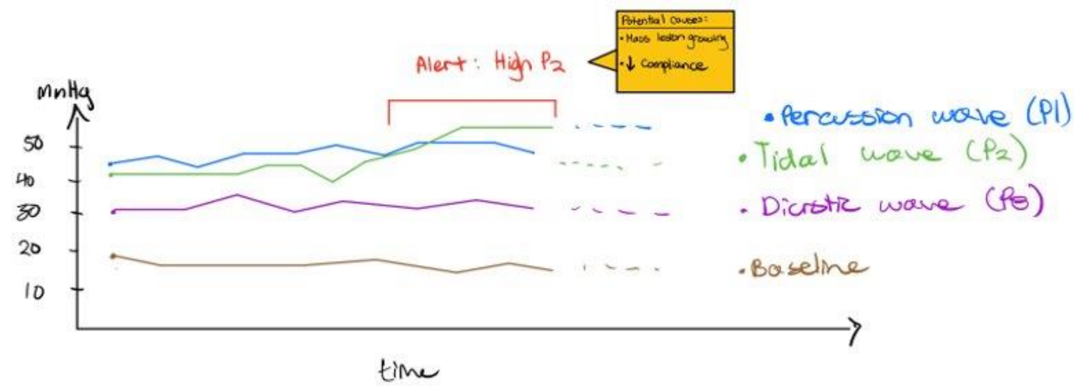


Figure 8: ICP Waveform Trend Chart

The separate trendline for each peak intends to make the peaks more obvious and provide mental context for the value of each peak and what they mean in comparison to one another. In the ICP waveform trend chart, the waveform peaks may be similar in value which would make it challenging to detect changes. Despite advances in signal processing, extracting the ICP waveform still poses numerous challenges including ICP signal characterization, model fitting, artifact detection, and model development and algorithm construction (Dai et al., 2020).

3.3.2 Connected Waveform Peaks to Detect Abnormal ICP

The second preliminary visualization, connected waveform peaks to detect abnormal ICP, also focuses on the ICP waveform peaks and highlights the differences between normal and abnormal ICP peak patterns. In normal conditions (healthy brain), P1 is expected to be the highest followed by P2 and then P3 as represented on the left in Figure 9. The left side of Figure 9 depicts abnormal ICP where P2 is higher than P1 indicating poor cerebral compliance.

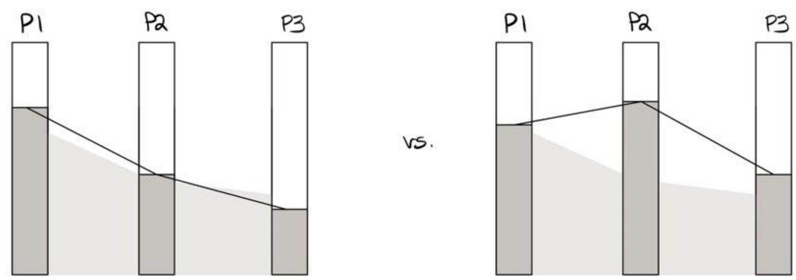


Figure 9: Connected waveform peaks to detect abnormal ICP (left- normal ICP, right-abnormal ICP)

Behind the bars, the light grey shaded area represents the expected values of each peak when ICP waveform physiology is normal. When the line which connects the three dark grey bars (actual ICP waveform peaks) varies from the light grey area, this indicates abnormal conditions.

Compared to the ICP waveform trend chart, this visualization displays only one set of waveform peaks which makes it easier to display the differences. All users may not be aware of the normal waveform behaviour, so the light grey shaded area provides a visual cue of waveform peaks in normal conditions. This visualization does not have a temporal aspect therefore, changes over time would require the user to integrate this information. For this visualization, similar challenges exist with waveform extraction. An additional model would also be required to calculate the light grey area or the expected waveform under normal conditions.

3.3.3 Summation Trend Chart

The third preliminary visualization, the summation trend chart, is a visual representation of the key hemodynamic equation and the role autoregulation plays in this equation. The key hemodynamic equation is that the sum of CPP and ICP is equal to the arterial blood pressure (or the mean arterial pressure, MAP). When a patient's autoregulation is intact, ICP should remain stable as the arterial blood pressure adjusts to make up for changes and spikes in the CPP (Silverman & Peterson, 2022).

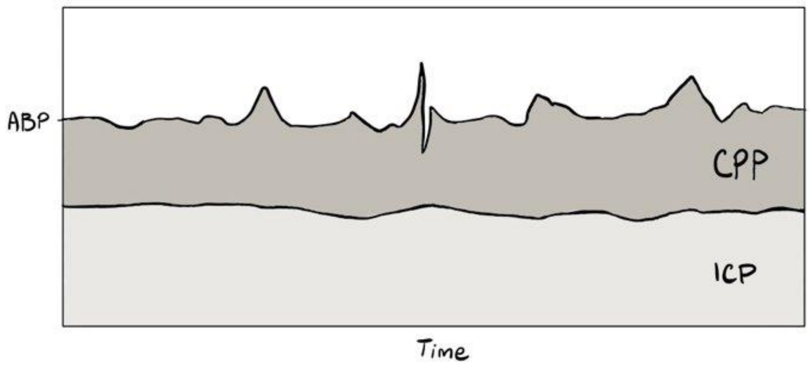


Figure 10: Summation Trend Chart

Stacked graphs have been criticized for their distortion of the baseline of the variable that is not at the bottom of the stack (Thudt et al., 2016). However, the purpose of this visualization is to highlight the key relationship and help users understand the relationship between MAP, CPP, and ICP. This visualization is an example of a multivariable display option for use on ecological displays (Burns & Hajdukiewicz., 2004). Burns & Hajdukiewicz (2004) acknowledge the limitation of this visualization is reading the variable at the top of the area (ICP).

3.3.4 ICP Dose Histogram

The fourth preliminary visualization, the ICP dose histogram, shows the amount of time a patient is spending at various ICP ranges in the past hour (Figure 11). Studies conducted on the impact of elevated ICP and duration on patient outcomes have revealed that the relationship between elongated periods of high ICP and worse outcomes is exponential in adult and pediatric populations (Kawoos et al., 2015). For example, a patient will be able to tolerate a moderately elevated ICP of 25mmHg for a longer period before long-term damage than a highly elevated ICP of 40mmHg.

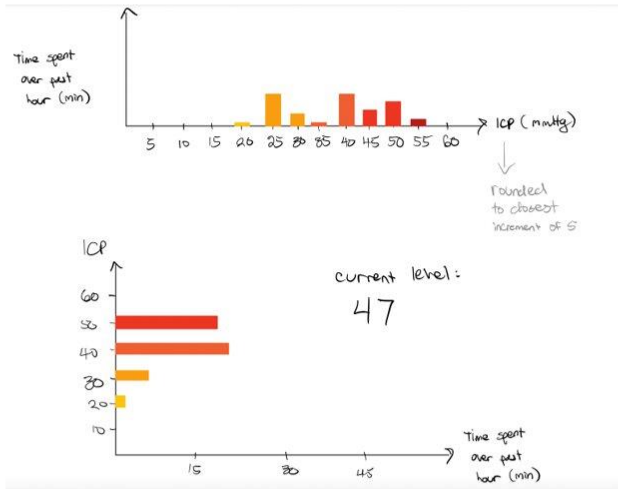


Figure 11: ICP Dose Histogram

The ICP dose histogram does not show any aspect of time so therefore, it serves as more of a summary for one point in time. To understand how the patient is doing over time and the trend, the user would need to look at multiple dose histograms and integrate this information.

3.3.5 Preliminary Visualization Summary (Version 1)

The preliminary visualizations (version 1) were designed based on the CWA and each visualization aimed to satisfy different elements in the AH on multiple levels. Table 1 summarizes the version 1 designs and some of the level 5 AH elements that are captured.

Table 1: Design summary of the preliminary visualizations (version 1) and AH elements

		ICP Waveform trend chart	Connected waveform peaks to detect abnormal ICP	Summation Trend Chart	ICP Dose Histogram
AH Elements	Patient Type (i.e., adult, or pediatric)			X	X
	Patient condition (i.e., obese, elderly)	X	X	X	X
	Disease (type and state)	X	X	X	X
	Damage (type, amount, and location)	X	X	X	X
	Relationship between multiple variables			X	
	Signals (frequency, amplitude, location, waveform)	X	X		
	Technology (visualization via screen, computers)	*Satisfied by multimodal monitoring*			
	Data Retrieval (past, current)	*Satisfied through interface interaction (i.e., customization and time scaling of graphs)*			
	Storage Capacity	*Satisfied by interface storage capacity (storage of historical data)*			

The last three elements-technology, data retrieval, and storage capacity-are not represented in individual visualizations but rather by use of multimodal monitoring, interface interactions, and storage capacity of the interface. These elements cannot be captured by static visualizations but are considerations in the final design outlined in Chapter 6.

3.4 Design Evolution

Conversations with our subject matter expert, Dr. Victoria McCredie led to a deeper focus on three neurophysiologic concepts and eventually iterated the following preliminary designs (version 2 visualizations). The three neurophysiologic concepts are outlined below in Section 3.4.1.

3.4.1 Key Neurophysiologic Concepts

A key goal of neuro-critical intensive care management is to minimize secondary brain injury. Three neurophysiologic concepts can be used to help ensure the secondary injury is prevented. These concepts include individualized thresholds, secondary insult dose, and the trajectory of the patient.

ICP management is not ‘one size fits all’ and these three concepts help support a more personalized approach to ICP management (McCredie, 2019).

3.4.1.1 Individualized Thresholds

In healthy adults, ICP is usually between 5-15mmHg. When ICP rises above 20mmHg, this would be considered intracranial hypertension (Rangel-Castillo et al., 2008). However, there are many circumstances when these standard ranges do not apply. If a mass lesion is present in the brain cavity, herniation can occur with ICP values of less than 20mmHg, and for a patient with hydrocephalus- characterized by an abnormal accumulation of CSF in the brain- ICP values greater than 15mmHg can be considered elevated (Czosynka & Pickard, 2004). As a result of these deviations from standard ranges, coming up with a universal ‘normal’ is challenging (Czosynka & Pickard, 2004). ICP is also impacted by age, body posture, and clinical conditions including specific pathology. Intracranial hypertension is a major cause of secondary brain injury and therefore, ICP monitoring is critical in patients with traumatic brain injury (Rangel-Castillo et al., 2008). There exists a need for individualized thresholds for ICP due to the importance of ICP as a monitoring tool and the fact that there are significant differences in the ‘normal’ range between individuals.

In a study conducted by Guiza et al, the researchers examined how cerebrovascular autoregulatory status impacts ICP thresholds (Guiza et al., 2015). For patients with traumatic brain injury (TBI), autoregulation is often impaired. The authors looked at how ICP intensity and duration curves are impacted when cerebral autoregulation is intact and when it is impaired and compared these curves. The results for adult patients can be seen in the Figure below.

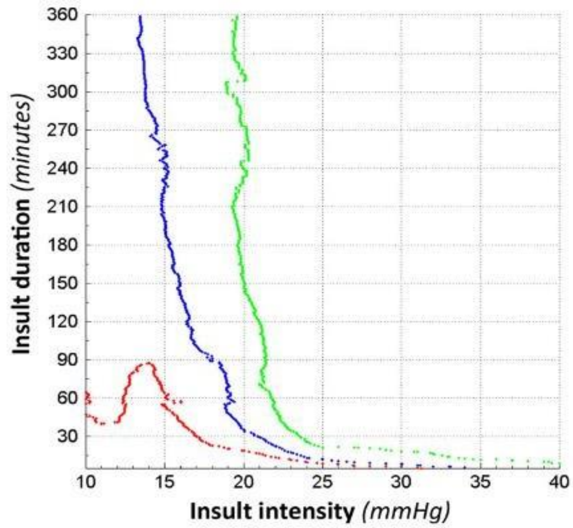


Figure 12: Insult (Transition) curve dependent on autoregulatory status. The blue curve represents all patients, the red curve represents impaired autoregulation, and the green curve represents intact autoregulation (Guiza et al., 2015)

In Figure 12, the blue line represents the insult curve including all patients and the red and green curves represent the insult curve for patients with impaired and intact autoregulation respectively. These results suggest that a patient with impaired autoregulation has a higher vulnerability to elevated ICP and there is a significant difference between a patient with intact versus impaired autoregulatory mechanisms. This study is an example of how individualized ICP thresholds are critical in providing care to TBI patients.

3.4.1.2 Secondary Insult Dose

Primary brain injury is referred to as the sudden injury that happens at the time of impact, such as a car accident or a fall whereas secondary injury happens due to changes that happen over the hours and days following a primary brain injury. In the neuro-critical ICU, treatment is given with the goal of secondary brain injury (John Hopkins Medicine, 2021).

The concept of ICP dose is explored and visualized in the Guiza et al. study titled Visualizing the pressure and time burden of intracranial hypertension in adult and pediatric traumatic brain injury. In previous research, the 'dose' concept of ICP has been proposed as the percentage of ICP measurements above 20mmHg or the area under the ICP vs time curve for hourly ICP values exceeding 20mmHg (Guiza et al., 2015). Guiza et al. explore how the duration and intensity of various ICP events (insults) impact patient outcomes. The study examined 261 adults (16+ years) with traumatic brain injury, their ICP and MAP monitoring data, and the Glasgow outcome scale (GOS) 6 months later. The GOS categorizes patients based on functional outcomes. A GOS score of 1 indicates death, 2 vegetative states, and 3-6 severe to moderate disability. Scores of 7 or greater indicate good recovery (Jennett & Bond, 1975).

The results were visualized by dividing the patients by GOS category and taking the number of average insults above an intensity and duration threshold. For each intensity and duration combination of a given GOS category, the correlation coefficient was computed. The coefficients were given a colour rating of dark red for a correlation of -1 and dark blue for a correlation of +1. In this study, a negative correlation represents an insult that occurs more frequently with lower GOS (worse outcome), and a positive correlation represents an insult that occurs more frequently with a higher GOS (better outcome). The results for adult patients can be seen in the Figure below.

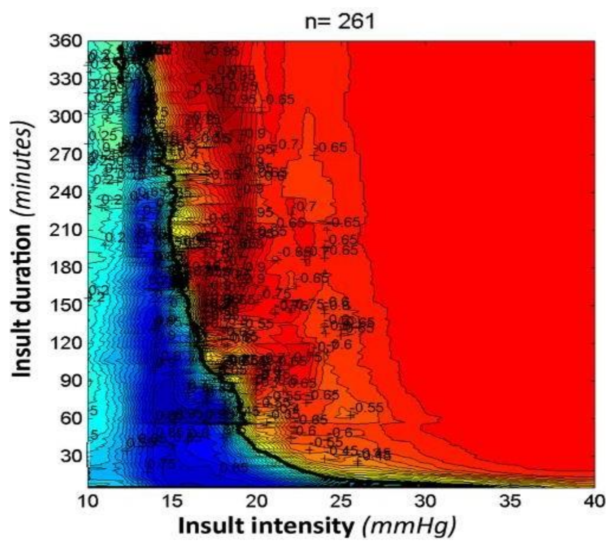


Figure 13: Visualization of the correlation between GOS and the average number of ICP insults per GOS category. Adult cohort (N=261) (Guiza et al., 2015)

In Figure 13, the transition line is defined as the black exponential decay line. The transition line is described by a correlation of zero and represents the transition from insult dose(s) that occur more frequently with patients with lower GOS versus higher GOS. These results indicate that patient outcome is heavily impacted by not only ICP intensity but also duration. At an insult intensity of 15mmHg, the transition curve approximates a vertical line with long durations which indicates that at what has previously been described as 'normal' ICP (15mmHg), sufficiently long durations can lead to poor outcomes. At an ICP intensity of 20mmHg, insults of greater than 37 minutes lead to worse outcomes, and above 25mmHg, the duration is only 12 minutes. These results indicate a need to not only look at the ICP threshold but also at the duration as there is a strong correlation between insult duration and outcome.

3.4.1.3 Trajectory

The third main concept in neuro-critical care monitoring is understanding the trajectory of the patient. To help explain this concept, an understanding of the ICP-volume curve is important. The pressure-volume curve has four key zones. These zones are described in Figure 14.

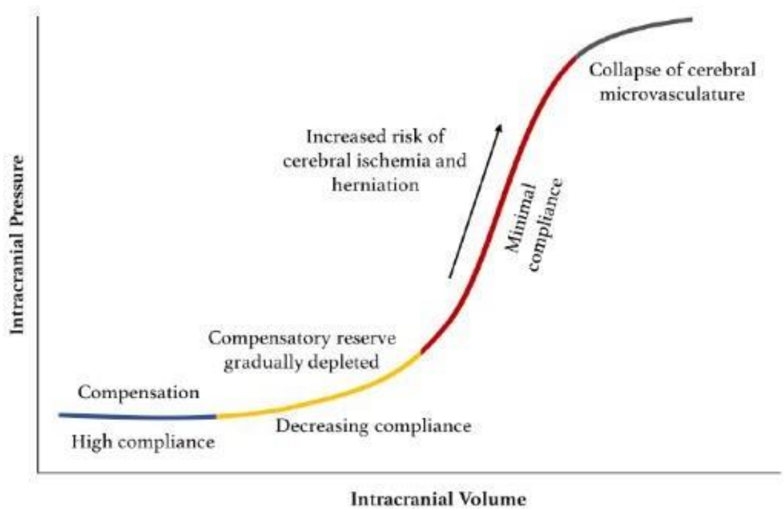


Figure 14: "Pressure volume curve for ICP. The pressure-volume curve has four 'zones': (1) baseline intracranial volume with a good compensatory reserve and high compliance (blue); (2) gradual depletion of the compensatory reserve as intracranial volume increases (yellow); (3) poor compensatory reserve and increased risk of cerebral ischemia and herniation (red); and (4) critically high ICP causing a collapse of cerebral microvasculature and disturbed cerebrovascular reactivity (grey)." (Harary et al., 2018)

The pressure-volume curve shows that on the left side of the curve, small increases in volume result in little to no change in pressure. This is a result of the compensatory reserve. On the right side of the curve, small changes in volume result in large changes in pressure. If clinicians can better understand where the patient is currently on this curve, treatment can be adjusted. It is easier to provide treatment when the patient is closer to the left side of the curve before the rapid rise in ICP (following decompensation).

Another example that highlights the importance of trajectory is looking at the stability of ICP. If a patient has ICP that is elevated (above 20mmHg) but steady, this may be less concerning than a patient that has ICP that has risen from 9mmHg to 19mmHg. Without looking at the ICP trend, it is impossible to know that the patient who has an ICP of 19mmHg needs to be examined more closely. This also ties into the concept of individualized thresholds.

3.4.2 Version 2 Visualizations: Design Iteration with Neurophysiologic Concepts

The preliminary visualizations (version 1) were iterated to capture the three key concepts outlined in the previous section. The below table shows the preliminary visualizations, and which neurophysiologic concepts are captured in the preliminary designs.

Table 2: Design summary of preliminary visualizations (version 1) and key neurophysiologic concepts

		ICP Waveform trend chart	Connected waveform peaks to detect abnormal ICP	Summation Trend Chart	ICP Dose Histogram
Key Neurophysiologic Concepts	Secondary Insult Dose				X
	Individualized Thresholds				
	Trajectory	X		X	

As seen in Table 2, the concept that is not captured in the first version of the designs is the concept of individualized thresholds. The goal of the design iterations was to capture all the key neurophysiologic concepts (secondary insult dose, individualized thresholds, and trajectory) as well as the elements in the AH.

The two version 1 visualizations that focus on ICP waveform data (ICP waveform trend chart and connected waveform peaks to detect abnormal ICP) were not carried forward in the next phase of design due to technical feasibility constraints previously discussed. However, it is recommended that these waveform visualizations be carried forward as future work considerations. A new visualization was designed to capture the individualized threshold concept and an additional trajectory visualization was designed for a summary view. The following sections outline the results of the first round of design iterations (version 2) and the incorporation of key neurophysiologic concepts.

3.4.2.1 Secondary Insult Dose

The ICP dose histogram preliminary visualization was the first iteration of a design that focused on the duration of ICP events. One drawback of the dose histogram is the lack of a temporal axis. The importance of trending dose over time is very important for patient management and therefore, this needed to be considered in a visualization. Moberg solutions (discussed previously in Section 2.3.2) is one monitoring company that explored visualizing ICP dose over time with multiple pie charts (Sihna et al., 2017).

Studies have shown that multiple pie charts-two or more pie charts that present the same ways of categorizing data for two or more groups-are not effective at comparisons unless the proportions change drastically (Kozak et al., 2015). This design asks the user to compare quantities located in spatial disarray both between and within pies by assessing angles and areas (Kozak et al., 2015). On the other hand, bar charts require that the user compare lengths and research suggests that proportional bar charts are easier to interpret and perform comparison than multiple pie charts (Siirtola, 2019). Pie charts are effective when there are no more than five proportions and when no comparison between multiple pie charts is required (Tolbert et al., 2018).

The ICP dose graphs (bar chart and summary donut) explore visualizing dose over time using stacked bar graphs and a donut graph for a summary. Based on discussions with Dr. McCredie, three ranges for ICP intensities were determined: normal, transitional, and high ICP. These three ICP intensities make up the three proportions of the ICP dose visualization described in Figure 15 below. Green represents normal ICP (<15mmHg), yellow represents transitional ICP (15-20mmHg), and red represents high ICP (>20mmHg).

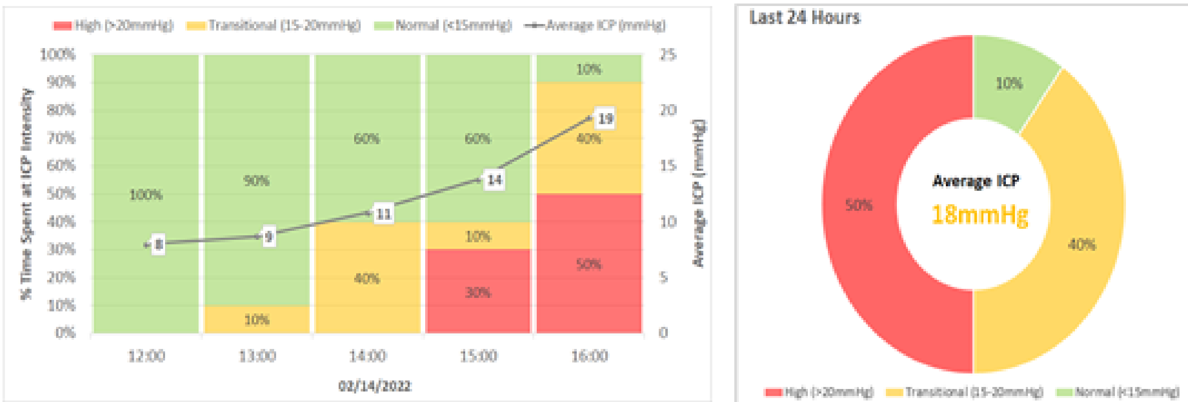


Figure 15: ICP dose visualizations. The left bar chart shows the ICP dose for 1 hour over time. The right visualization is a donut chart that shows the ICP dose for 24 hours.

The left bar graph (Figure 15) shows the amount of time that a patient spent at each ICP intensity for 1-hour periods. Each bar represents 1 hour, and the proportions of the bar show the percentage of time the patient spent in that ICP intensity. The bars and proportions are read by the left axis and the high ICP area is always visualized at the bottom, transitional always in the middle, and the normal ICP at the top. The line overlayed on the bars represents the average ICP for the hour and the line is read on the right y-axis. The average line is provided to help visualize the trend in ICP in addition to the bar graph proportions. The right donut graph (Figure 15) is an alternative representation of the dose concept without the temporal aspect. The intention is for the donut visualization to be used in conjunction with the bar chart visualization to offer a summary.

In the static version of the bar chart and donut chart visualizations, the ICP intensities are set to default ranges, however, in an interactive interface, the intention is that there would be functionality for these ranges to be adjusted from patient to patient recognizing the importance of the individualization of thresholds. Time scaling customization would also be available on an interactive interface where the user could adjust the time scale of the x-axis on the bar graph or the time-scaling on the donut graph.

3.4.2.2 Individualized Thresholds

The individualized threshold concept was not captured in the preliminary visualizations. Therefore, some new designs were created to capture the concept. The individualized threshold visualization depicted in Figure 16 aims to show where the patient came from and highlights the individualized ranges of normal, transitional, and high ICP for a patient.

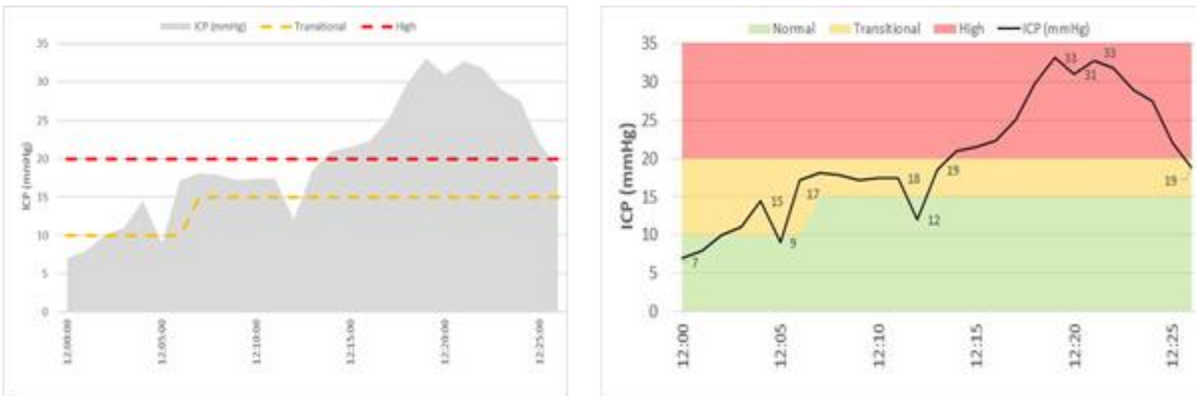


Figure 16: Individualized threshold visualization

The x-axis is the timeline, and the y-axis is the patient's ICP. The colour coding represents three ICP intensities: normal in green, transitional in yellow, and high in red which are consistent with the ICP dose visualization (Figure 15). These ICP intensity targets can be customized and at 12:08, a target change from 10 to 15mmHg for the patient's transitional ICP is depicted. The right representation shows the thresholds for transitional and high ICP as dashed lines, and the left representation shows the normal, transitional, and high ranges as the background of the graphic. Time scaling customization would be available on an interactive interface where the user could adjust the time scale of the x-axis to show a larger (or smaller) period.

3.4.2.3 Trajectory

Research suggests that there is value in providing trend information at the bedside for key physiologic parameters through the display of graphic trendlines or graphical indicators (Tappan et al., 2009) (Kennedy & Merry, 2011). Current interfaces lack trend information, present trend information in a tabular form, and sometimes across multiple screens, and therefore there is a high mental load required to integrate this information (Anders et al., 2012).

The first version of visualizations captured the key neurophysiologic concept of trajectory as they showed ICP changes over time, however, changes over a longer time can be challenging to detect. Discussions with Dr. McCredie revealed that novices tend to take a numerical approach to ICP management and have the tendency to overlook patients that may have an ICP that is below a threshold even though the patient's trend is worrisome (McCredie, 2019). This led to the design of a visualization that could act as an alert for novices to pay attention to a patient who has an ICP that is below a threshold but rapidly rising. For example, a patient that has a high ICP (above 20mmHg), yet stable may be less concerning than a patient that has an ICP that has risen from 9 to 19mmg, despite 19mmHg still being in the transitional range.

The trajectory visualization shown in Figure 17 focuses on the percent change in ICP and helps indicate the trajectory the patient is on. Since every patient has a different threshold for ICP management, percent change is a more individualized approach. Rather than looking at the current value of ICP, the change in ICP value is represented. If a patient has a rapidly rising ICP (large percent change) and the actual ICP value is below the threshold of 20mmHg, the visualization aims to give a cue to the clinician that the trajectory of the patient is of concern.

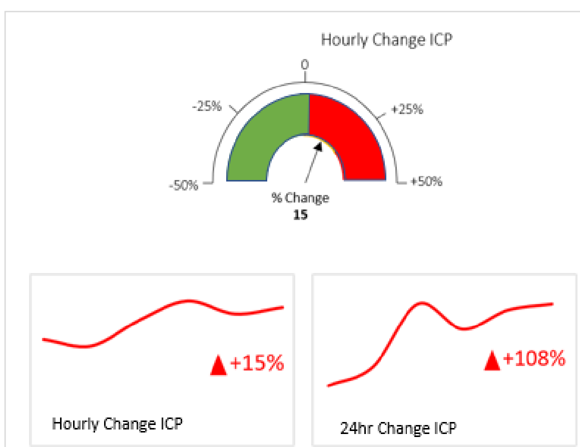


Figure 17: Trajectory

The top visualization (gauge or speedometer design) shows how ICP has changed in the past hours. ICP percent change of greater than zero is more concerning and the colours represent an increase in ICP as red and a decreasing ICP as green. The bottom two visualizations show the previous hour's trend and the last 24-hour trend and the corresponding percent change over that time frame. Time scaling customization would be available on an interactive interface where the user could adjust the time scale of the trajectory visualizations to show a larger (or smaller) period. Percent change normalizes a patient to a baseline and considers their starting or ending point. This has the benefit of being more individualized, however, there are no current guidelines on what percent change needs to be acted upon. This visualization will need to be integrated with other information to help with a greater understanding of the risks associated with a patient and what trajectory they may be on.

3.4.2.4 Summation Trend Chart

The summation trend chart visualization is a continuation of version 1 visualization. This visualization captures the concept of trajectory and highlights an important relationship in neurophysiology. The version 1 summation trend chart was given colours that are distinctly different that the previous visualizations, so the user is aware that a new concept is being shown. Rather than showing a conventional legend, the equation for MAP, CPP, and ICP is shown above the graph to make this relationship clear, especially for novice users.

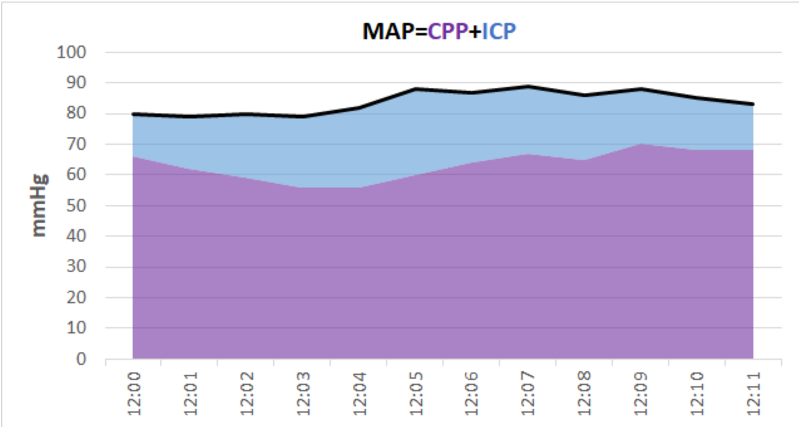


Figure 18: Summation trend chart for ICP, CPP, and MAP

As previously discussed, stacked graphs have their challenges with perception but with EID, the intent is to make relationships more visible for the user and the summation graph illustrates the important hemodynamic relationship.

3.4.3 Version 2 Visualization Summary

Version 2 of the visualizations were designed based on the CWA and the integration of the key neurophysiologic concepts. Table 3 summarizes the version 2 visualizations and some of the level 5 AH elements and neurophysiologic concepts are captured.

Table 3: Design summary of version 2 visualizations, AH elements, and key neurophysiologic concepts

		ICP Dose-Bar and Donut chart	Individualized Thresholds	Trajectory	Summation Trend Chart
AH Elements	Patient Type (i.e., adult, or pediatric)	X	X	X	X
	Patient condition (i.e., obese, elderly)	X	X	X	X
	Disease (type and state)	X	X	X	X
	Damage (type, amount, and location)	X	X	X	X
	Relationship between multiple variables				X
	Signals (frequency, amplitude, location, waveform)				
	Technology (visualization via screen, computers)	*Satisfied by multimodal monitoring*			
	Data Retrieval (past, current)	*Satisfied through interface interaction (i.e., customization and time scaling of graphs)*			
	Storage Capacity	*Satisfied by interface storage capacity (storage of historical data)*			
Neurophysiologic concepts	ICP Dose	X			
	Individualized Thresholds	X	X		
	Trajectory	X	X	X	X

The signals element including frequency, amplitude, location, and waveform are not captured in the version 2 visualizations. The results of the CWA indicated the importance of ICP waveform, however technical feasibility of extracting the waveform peaks resulted in the discontinuation of these visualizations for this work.

The version 2 visualizations were used in semi-structured interviews with both fellow and staff physicians in neuro-critical care to address usability concerns, iterate the designs further, and refine the designs. The preliminary usability assessment with trainees is discussed in Chapter 4 and the design refinement and feedback elicitation with experts is discussed in Chapter 5.

Chapter 4
Preliminary Usability Assessment

This next chapter outlines the method and results of the initial evaluation and usability assessment of the low-fidelity visualizations conducted with trainee physicians. The goal of the preliminary usability assessment with trainees was to gather feedback from the trainees on usability concerns of the visualizations so that these could be addressed in the final design.

4.1 Method

A preliminary usability assessment was conducted with trainee critical care physicians to gather feedback on usability concerns of the visualizations so that modifications and interface training could be adjusted accordingly. The interviews provided early feedback on the static designs before the combination of the designs on an interactive interface.

4.1.1 Semi Structured Interviews

The feedback was elicited through qualitative semi-structured interviews. The study received ethics approval through the University of Waterloo Research Ethics Board. Semi-structured interviews were selected due to their flexible designs (Fylan, 2005). This study was the second part of a longer interview including a discussion of expertise in neuro-critical care (in Figure 19, step 3), therefore, there was variability in the amount of time allocated to the interviews. Typically, 30 min was allocated to the visualization section of the interview and the entire interview time was 60 min. When more time was allotted, a more in-depth discussion was possible. However, there were also instances where some sections had to be skipped and the modular design of the study made this possible. The study protocol is described in Figure 19.

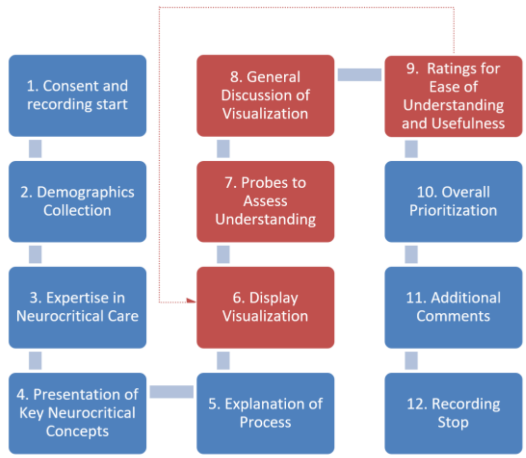


Figure 19: Interview Protocol for trainees

The semi-structured interviews were modular, and the visualization section of the interview consisted of seven main sections (described by steps 4 through 10 in Figure 19). For each visualization, steps 6-9 were repeated. The order in which the visualizations were presented was the same for each participant: 1) ICP dose (bar and donut), 2) individualized thresholds, 3) trajectory, and 4) summation trend chart. As mentioned, due to time limitations, there were instances where not all visualizations were discussed with the participants. The seven main sections of the interview are described in greater detail in Table 4 below.

Table 4: Description of key steps in the visualization section of the semi-structured interviews with trainees

#	Step Name	Description
4	Neurophysiologic Concepts	Participants were presented with three concepts of neuro-critical care which the visualizations aimed to capture.
5	Process Explanation	The interviewer explained the process that would take place for each visualization (general description of steps 6-10).
6	Display Visualization	Participants were presented with the static visualization without any explanation (e.g., axes, colour coding, interpretation). Participants were asked to describe the visualization in as much detail as possible and when two representations of visualizations were shown, the participants were asked to describe both.
7	Probes to Assess Understanding	To assess the participant's understanding of the visualization, probes were used such as "*Can you explain how you interpret the percentages?".* These probes would allow later scoring of the participants' understanding.
8	General Discussion	The interviewer explained the visualization to the participant and facilitated a general discussion about the visualization.
9	Ratings (Ease of Understanding & Usefulness)	Participants were asked to score visualization on a 1-5 scale on ease of understanding and usefulness (1-poor, 5-excellent).
10	Overall Prioritization	At the end of the interviews, the participants were shown all the visualizations again and asked to prioritize which visualization(s) they would appreciate most on a bedside physiologic monitor. It was emphasized that they could choose multiple or none depending on their preferences.

The interviews were conducted virtually over Microsoft teams with two interviewers (KS and EU) on the call and one interviewer asking the questions. The participants were given consent and demographic questions before beginning the session. Refer to Appendix A for the recruitment materials, information letter, and remuneration letter and Appendix B for the questions posed in semi-structured interviews.

4.1.1.1 Participants

Participants were recruited through subject matter expert and critical care physician, Dr. Victoria McCredie. The participants were sent an invitation to sign up for the study which included the goal of the study, remuneration amount, study requirements, and a Calendly link to sign up for a 60 min interview (30 min allotted to preliminary usability assessment of visualizations). A total of 18 participants were interviewed as part of this study. All the participants were current trainees (fellows) in critical care and had some experience with ICP monitoring. The table below shows the demographics of the 18 participants interviewed. Year of training represents the number of years in critical care training in Canada and the country indicates where the physician is current training.

Table 5: Demographics of the Trainees

T#	Age	Gender	Year of training (in CC)	Specialty	Subspeciality (pending)	Country
T1	ND	F	1	Internal Med Cardiology	Critical Care	CA
T2	35	F	1	Emergency Med*	Critical Care	CA
T3	31	M	1	Emergency Med*	Critical Care	CA
T4	34	F	1	Internal Med	Critical Care	CA
T5	34	F	2	Internal Med* Pulmonology*	Critical Care	CA
T6	47	M	2	Internal Med*	Critical Care	CA
T7	39	F	1	Cardiology* Immunology*	Critical Care	CA
T8	36	F	1	General Surgery*	Critical Care	CA
T9	36	F	1	Anesthesia*	Critical Care	CA
T10	34	M	2	Internal Med*	Critical Care	CA
T11	30	M	1	Internal Med	Critical Care	CA
T12	35	F	4	Anesthesia*	Critical Care	CA
T13	31	F	2	Anesthesia	Critical Care	CA
T14	29	F	1	Internal Med	Critical Care	CA
T15	31	F	1	Emergency Med*	Critical Care	CA
T16	30	M	1	Emergency Med*	Critical Care	CA
T17	30	M	1	Critical Care*	Critical Care	CA
T18	34	F	2	Anesthesia* Critical Care*	Critical Care	CA

* Indicates certification received in another country.

4.1.1.2 Analysis

After the interviews were conducted, the Microsoft teams recording were transcribed using the Microsoft team's transcription software. The interviews were summarized, and any relevant quotes were included in this summary which was sent back to the participant for review. The summary was sent to the participant and the participant was asked to provide comments as required. This process was followed to provide the participant with the opportunity to clarify or make changes if they believed anything in the summary was documented incorrectly. The recordings, transcripts, and summaries are stored on a password-protected OneDrive owned by the authors (KS and EU) and used later in data analysis.

The interviews were analyzed using inductive thematic analysis. Thematic analysis can be described as the process of identifying patterns and themes in qualitative data (Braun & Clarke, 2012). The qualitative data was coded inductively, meaning that the codes were derived from the data. To increase the reliability of the qualitative analysis, the interview coding was first done by researcher KS and then reviewed with interviewer EU. The general process followed to analyze the interviews can be described by the steps below (Braun & Clarke, 2012):

1) **Familiarization with the data:** This step involved reviewing the video recordings of the interview, summarizing the interview, and including relevant quotes, sending the summaries to the interviewees for review, and adjusting the summaries with any feedback from the participants. This step was taken after each interview and after all the interviews had been conducted. After each interview, the interviewers (KS and EU) discussed early impressions.

2) **Generating initial codes:** This step was used to start organizing the interview data and group comments made in the interview that had similar meanings or topics. The codes were generated inductively meaning that codes were derived from the interview data rather than a predetermined set of codes. This step was done by taking the interview summaries and quotes and separating the different topics line by line and grouping them by similar topics. Interviewer, KS, worked on the initial codes independently and these were later reviewed with EU.

3) **Searching for themes:** This step involved examining the initial codes and identifying any codes that fit together into a theme. This was done for each visualization and additionally, a general category that did not align with a specific visualization. For some codes, there was an overarching theme and then subthemes to provide an additional level

of hierarchy to group the codes. At the end of this step, the codes are organized into broader themes and subthemes.

4) **Reviewing themes:** In this step, the interviewers (KS and EU) reviewed, modified and developed the preliminary themes. The excel sheet was used to sort by each theme and subtheme and evaluate whether the comments in each category made sense. In this step, the themes and subthemes were reviewed by each visualization and globally to understand the overlap across the visualizations. For example, several comments came up in multiple visualizations around the desire for simplicity and therefore, this subtheme was regarded as a more general theme.

4.2 Results

The interviews with trainees were coded by each visualization and globally (evaluating all visualizations together). Table 6 includes the themes and subthemes that emerged for each visualization.

Table 6: Themes and subthemes from interviews with trainees for each visualization. Bolded subthemes appeared across multiple visualizations.

Visualization	Theme	Subtheme
ICP Dose	Visualization Usability	- Interpretation of ICP burdens and percentages - Wording of y-axis - Two axes in context with graph description
	Visualization Application	- Trend - Complimentary
	Distribution of ICP Values	- Average - Fluctuations in ICP
	Impact on Management	- **Transitional Threshold**
	General Usability	- Intuitiveness - **Desire for Simplicity** - **Collation of Information**
	Visualization Interaction	- **Time Scaling** - **Target Customization**
Individualized Thresholds	Visualization Usability	- Detection of threshold change - Interpretation of the colours of ICP intensity ranges
	Content Feedback	- Annotations
	Design Preferences	- Familiarity - Ease of Understanding - Salience
	Impact on Management	- **Transitional Threshold**
	General Usability	- **Desire for simplicity** - **Collation of Information**
	Visualization Interaction	- **Target Customization** - **Exact Values**
Trajectory	Visualization Usability	- Interpretation of percent change - Implication of percent change - Trendline Visualization - Gauge Visualization
	Visualization Application	- Training - **Integration with other visualizations** - Alert
	Visualization Interaction	- **Time Scaling** - **Exact Values**
Summation Trend Chart	Visualization Usability	- Challenges identifying individual variables - Legend
	Content Feedback	- Importance of CPP targets
	Visualization Application	- Relationship of variables - **Integration with other visualizations**
	Visualization Interaction	- **Time Scaling** - **Exact values**

The following Sections 4.2.1-4.2.4 discuss the trainees' understanding, themes, and subthemes for the visualizations and the ease of understanding and usefulness ratings. The bolded subthemes in Table 6 appear across multiple visualizations and will be discussed in Section 4.2.5 along with other general comments that were visualization agnostic.

4.2.1 ICP Dose

4.2.1.1 Assessing Understanding

To assess understanding, the participants were presented with visualizations (bar chart and donut chart) without any explanation, and they were asked to describe the visualization in as much detail as possible. When appropriate, the participants were probed with questions such as "*Can you describe to me what the percentages on the bars represent?*" or "*Can you tell me how you interpret the colours?*" The understanding scores were calculated by analyzing the transcripts and recordings and giving the participant a score of 0 or 1 for each element if they accurately understood the element of the visualizations including the colour coding, average ICP, ICP trend, and the ICP dose percent. The understanding scores were tabulated for the ICP dose and can be seen in Table 7 below.

Table 7: Understanding Scores for ICP Dose Visualizations

Understanding Scores	*Colour Coding*	*Average ICP*	*Dose Percent*	*ICP Trend*	*Total Score*
ICP Dose n=18	78%	89%	56%	94%	**79%**

The element that the trainees had the hardest time describing was the dose percent followed by the colour coding of the ICP intensities and the average ICP. These areas of confusion are discussed further in the thematic analysis of the interviews.

4.2.1.2 Themes

Table 8: Themes and subthemes for the ICP Dose Visualization (Trainees)

Theme	Subtheme	Description, Quote, or Example
Visualization Usability	Interpretation of ICP burdens and percentages	Any comment where there was trainee confusion on how to interpret the bar graph percentages and burdens or misinterpretation when they were asked to explain it. *"100% of the hour from 12 to 1 (12:00-13:00) they were just at 8 (mmHg)" T18*
	Wording of y-axis	Visualization usability regarding the wording of the left y-axis of the bar graph (percent time at ICP intensity). *"Percent time at ICP intensity…. I am not sure I fully understand that." T4*
	Two axes in context with graph description	Any visualization usability comments made about multiple y-axes of the bar chart. This includes any comments made about the stacking order of the ICP intensities. *"That kind of threw me a little bit because on the right-hand side on the y-axis, the higher the number, the higher the ICP so you are kind of processing two directions at the same time. So, I think I kind of expected the high to be mapping with the high." T4*
Visualization Application	Trend	Any comment that discussed the importance of the patient's trend in visualizations. *"My brain is trained to think in a temporal axis for all physiological parameters." T4*
	Complimentary	Comments that acknowledged the different applications of the bar and donut graph and although different, they both provide value and are complimentary. *"They probably serve different purposes." T2*
Distribution of ICP Values	Average	The average subtheme included comments made by trainees about the utility of showing an average value of ICP. *"A mean ICP may not necessarily convey all of the nuances that may need to be addressed." T1*
	Fluctuations in ICP	Any comments that were made about the fluctuations in ICP values and desire to show a range and peak values. The physician commented that if they were told that ICP was 14mmHg, they would not be worried but if they saw peaking values of 24mmHg, this would be concerning. *T18*
General Usability	Intuitiveness	Comments that were made by the trainees around how to use the visualization and how easy it was to understand. *" I am still struggling a bit with understanding how to translate it and use it appropriately." T10*

Visualization Usability

Visualization usability arose as a theme in the interviews with trainees. The three subthemes for visualization usability were identified as the interpretation of the ICP burdens and percentages, the wording of the left y-axis, and two axes in context with the graph description. Several trainees struggled to interpret the ICP burdens and percentages, and they were unable to describe what the visualization was telling them as indicated by the understanding scores in Section 4.2.5. The trainees had various misinterpretations of the percentages and below are a few examples:

- One physician thought that the percentages represent the amount of time a physician spends monitoring ICP in each respective range. "*So, let's say you take the normal one which is 100% green, so I thought 30% of our time is spent monitoring patients that we know are generally within the normal ICP, but when the ICPs go higher and become more critical, that the time spent at the ICP monitoring is higher." T13*

- Two physicians misinterpreted that if the average line was inside the green or normal area of the bar graph, this indicates that the average is in the normal range whereas, in reality, the average line was intended to be read on the secondary y-axis. *"100% of the hour from 12 to 1 (12:00-13:00) they were just at 8 (mmHg)." T18*

- One physician thought that the percentages and ranges corresponded to the percent risk that the ICP would be in that respective range. *T3*

- One physician interpreted the percentages as a percent increase of that respective range. For example, if at one hour the patient had a transitional proportion of 10%, that indicated that the transitional ICP proportion had increased by 10% in that hour. *T8*

Another area of confusion was the wording of the left y-axis, percent time at ICP intensity. The trainees commented that they were unsure what the axis title meant, and this impacted their ability to accurately understand the visualization. Some trainees were able to examine the visualization and understand what the axis title meant by looking at other aspects of the visualization however, some trainees struggled with getting past the axis title.

"Percent time at ICP intensity…. I am not sure I fully understand that." T4

Some trainees were also confused about the two y-axes on the bar chart and comments were made about the axes being inverted. In the bar chart, the left y-axis is the percent time at ICP intensity and the high ICP proportion is visualized at the bottom of the stack (transitional in the middle and normal on the top) and the right y-axis visualizes the high average ICP at the top. This confused some of the trainees, however, many were able to resolve this confusion with closer examination.

"That kind of threw me a little bit because on the right-hand side on the y-axis, the higher the number, the higher the ICP so you are kind of processing two directions at the same time. So, I think I kind of expected the high to be mapping with the high." T4

Visualization Application

Another theme that emerged in the interviews with trainees was the application of the visualizations. The two subthemes for the application visualization theme were identified as trend and complimentary. The trainees explained that the bar chart shows more information as you can see the trend of a patient's ICP dose. In medicine, the aspect of time is very important, and physicians generally want to see information over time. One trainee even commented that if they had both the bar chart and the donut chart, they likely would not look at the donut chart or miss it if it were not present.

"This type of thing (referring to the donut chart) that take away the temporal x-axis are interesting, but they don't add to my clinical decision-making. It is almost like a factoid that is just there to look at for data visualization but is not something I would miss if it wasn't there…My brain is trained the think in a temporal axis for all physiologic parameters." T4

There was some concern that multiple scenarios could generate the same donut visualization. With the donut chart, it is impossible to know when over the time frame the patient had a high ICP, and more information is required.

"A lot of different scenarios can give you this chart (donut chart)." T12

One trainee commented that for the donut chart, if this was the only piece of information they saw, it may be too late to act on treatment. It is important to know the current state and trend of a patient to provide treatment and with elevated ICP, decisions must be made quickly.

"If I came in the morning and saw this graph (donut chart), it's too late because your patient had a dangerous ICP for more than half of the last day, so you are one day late." T17

Trainees consistently acknowledged the importance of a trend, and they appreciated that the bar chart showed the dose of a patient over time. Another common theme for comparing the bar chart and donut chart was that the charts have different purposes and are complimentary to one another. The trainees described the bar chart as being more applicable for acute changes, and the donut chart as being for longer-term windows of time.

"The first one (bar chart) would be more acute changes over a shorter period of time and then you can see whether a certain intervention worked or didn't work with that, whereas this one (donut) would be how the patient was doing over the last few days." T9

"That one (bar chart) is more short-term and more informative for management at that point, this one (donut chart) is probably more helpful for prognostication if the patient has already been 60-70% of the time in the higher range and it kind of informs me about where the patient is going and what their prognosis is." T10

There were also comments that the donut chart would be most useful as a summary or an overview in addition to the bar chart and although it may not be used to guide treatment, it is simpler and may provide value at patient handover or meetings with the family.

Distribution of ICP Values

It was acknowledged that ICP needs to be evaluated as more than a single value and that the distribution of the ICP values is important. The three subthemes for the distribution of ICP values were identified as average and fluctuations in ICP. Trainees commented that although the average ICP on the bar chart shows the trend of the patient, the average alone may not show the full context of ICP.

"A mean ICP may not necessarily convey all of the nuances that may need to be addressed." T1

Trainees also remarked that an average may also have the potential to be misleading without the distribution around the average. For example, if the average is below the threshold of concern (20mmHg) the physicians may interpret this as the patient being below the high ICP range however, the patient would have spent time above and below that average.

"You may think that it is safe if the ICP (average) was 8mmHg but then when you look at the percentage spent at each value it is dangerous." T7

The trainees explained that more than the average ICP, it is important to understand how much the patient's ICP fluctuates in the hour and the range is important. Some trainees mentioned that average plus standard deviation and range would provide more context of what is happening with the patient. One trainee described that if they knew the average of a patient was 14mmHg, they may not be worried but peaking values of 24mmHg would cause them to be concerned highlighting the importance of showing the maximum value of ICP. There was an acknowledgment that the spikes in the ICP and how long those spikes are sustained (dose) is useful and the peak values matter more than the minimum values.

General Usability

General comments were made around the usability of the visualizations and the main subthemes were identified as intuitiveness, desire for simplicity, collation of information, and monitoring type. The desire for simplicity and collation of information were both themes that appeared across multiple visualizations, therefore, these will be discussed further in Section 4.2.5.

There was mixed feedback on the intuitiveness of the dose visualizations. Some trainees struggled with understanding how they would use the visualizations and made comments that the visualizations were challenging to interpret and unfamiliar.

"I am still struggling a bit with understanding how to translate it and use it appropriately." T10

"It is not that user-friendly, and I am not getting used to this graph." T5

However, other trainees understood the visualization and found it intuitive and easy to understand, noting that it is immediately obvious that the patient's ICP is heading in the wrong direction.

"I love the colours, I love the percentages, and how it is presented because it is very visual, and you can see the moment when it begins to be dangerous." T7

4.2.1.3 Ratings

Following the general discussion of the visualization, the trainees were asked to rate the visualization on a scale from 1 to 5 on ease of understanding and usefulness. The results for these ratings can be seen below in Table 9.

Table 9: Ease of Understanding and Usefulness Ratings for ICP Dose Visualizations (Trainees)

	Mean	*Std Dev*
Ease of Understanding n=14	4.0	0.78
Usefulness n=14	4.7	0.46

4.2.2 Individualized Thresholds

4.2.2.1 Assessing Understanding

Following the same process as the ICP dose visualization, the understanding of the participants was assessed for the individualized threshold visualization. The participants were presented with an image of the visualization without any explanation, and they were asked to describe the visualization in as much detail as possible. When appropriate, the participants were probed with questions such as "*Can you describe to me how you interpret the colours?* or "*Can you comment on the values of the ICP targets?*" Understanding scores (0 or 1) were given to each element of the visualization including the target change, colour coding, and ICP trend. A total score was given to the participant by summing the score for each element. These scores were divided by the number of participants (n) evaluated to give an understanding score percentage. For example, if 13 participants of the 16 evaluated understood the ICP target change, the understanding score for this element would be 13/16 or 81%. The scores can be seen in Table 10 below.

Table 10: Understanding Scores for Individualized Threshold Visualization (Trainees)

	ICP Target Change	*Colour Coding*	*ICP Trend*	*Total Score*
Understanding Score n=16	81%	94%	100%	**92%**

As seen in Table 10, the element that the participants struggled with understanding the most was the ICP target change. This element was not always mentioned by participants in the interviews when asked to describe the ICP targets for the visualization. One participant did not understand the colour coding of this visualization when probed and the ICP trend was understood by all participants.

4.2.2.2 Themes

Table 11: Themes and subthemes for the Individualized Threshold Visualization (Trainees)

Theme	Subtheme	Description, Quote, or Example
Visualization Usability	Detection of threshold change	Comments that were made that noted confusion and detection of the threshold change for the transitional target. The physician noted that it is easy to miss the threshold in the transitional target. T17
	Interpretation of the colours of ICP intensity ranges	Visualization usability comments regarding how to interpret the colours for the ICP intensities. The physician noted that they were unsure what the colours represented. "*I don't know what the coloured part is." T15*
Content Feedback	Annotations	Any comment made about the value of annotating events such as medication administered or other treatments. Physicians commented that annotations on the graph would be helpful to understand the response to treatment. *T2*
Design Preferences	Familiarity	Comments made around a preference for a certain design based on familiarity with the design. The physician commented that the visualization is familiar with what they would see in the hospital. *T5*
	Ease of Understanding	Comments made around a preference for a certain design based on ease of understanding of that design. Physicians commented on which representation was easier for them to understand. Some preferred the dashed line representation of targets; others preferred the coloured blocked representation.
	Salience	Comments made around a preference for a certain design based on the salience of that design. "It just visually pops out at you in terms of normal, transitional, and high." *T1*

Visualization Usability

Visualization usability was identified as a theme in the interviews with the trainees, although not many comments arose in this category. As indicated by the understanding scores for the individualized threshold visualization compared to the ICP dose visualization (Table 7 and Table 10 respectively), trainees had a higher understanding of the individualized threshold visualization. The two subthemes for visualization usability of the individualized threshold visualization are the detection of threshold change and the interpretation of the colours of ICP intensity ranges. On the individualized threshold graph shown to the trainees, the transitional target changed from 10mmHg to 15mmHg. The trainees noted that this target change was not always apparent, and it is easy to miss.

The colours for ICP intensity ranges were consistent with the ICP dose visualization, therefore, this likely contributed to trainees having less confusion around the ICP target ranges and colours. However, one physician noted that they were unsure what the colours represented in the individualized threshold visualization.

"I don't know what the coloured part is." T15

Content Feedback

Any comments that arose on content included in the visualization and potential modifications were included as part of the content feedback theme. There was only one subtheme for this category, and it was identified as annotations.

Trainees explained that understanding how a patient is responding to treatment is very important and it would be useful to integrate annotation of events into the individualized threshold visualization. For example, if a medication was administered or another treatment was given, it would be valuable to be able to see these events on a graph so that they can understand what has been tried and if it was successful or not.

Design Preferences

The trainees were presented with two different versions of the individualized threshold visualization at the same time. The trainees typically preferred one visualization over the other but for different reasons. Three subthemes for design preferences emerged: familiarity, ease of understanding, and salience.

The trainees had an appreciation for the individualized threshold visualization because it was familiar to visualizations they have seen before. The individualized threshold visualization does not have calculated parameters (i.e., percent of the time at ICP intensity) but rather, presents the data in a raw form. One physician noted that they had a preference for the dashed line representation of ICP targets is familiar to something they would see in the hospital.

Ease of understanding was another subtheme that was identified. It was trainee dependent on which version of the visualization they found easier to understand. Some trainees preferred the colour-blocked representation, noting that it was more intuitive and easier to interpret. However, other trainees believed the dashed line representation was simpler and easier to understand.

Trainees generally acknowledged that the colour-blocked representation of the visualization was more salient than the dashed line representation. For some trainees, this resulted in them preferring the visualization.

"It just visually pops out at you in terms of normal, transitional, and high." T1

"(The coloured blocked representation) is more obvious from first look." T3

The trainees had all been previously shown the ICP dose visualization, so this may have impacted their preference for the colour-blocked representation as it was consistent with the design of the dose visualizations.

4.2.2.3 Ratings

Following the general discussion of the visualization, the trainees were asked to rate the visualization on a scale from 1 to 5 on ease of understanding and usefulness. The results for these ratings can be seen below in Table 12.

Table 12: Ease of Understanding and Usefulness Ratings for Individualized Threshold Visualizations (Trainees)

	Mean	*Std Dev*
Ease of Understanding n=13	4.38	0.85
Usefulness n=13	4.58	0.49

4.2.3 Trajectory

4.2.3.1 Assessing Understanding

Like the previous visualizations, the understanding of the participants was assessed for the trajectory visualization. The participants were presented with an image of the visualization without any explanation, and they were asked to describe the visualization in as much detail as possible. Probing questions such as *"Can you explain how you understand the percentages?"* or "*Can you explain how you understand the top gauge visualization?"* were asked to allow for assessment of their understanding. Understanding scores (0 or 1) were given to each element of the visualization including the meaning of the percent change, trendline interpretation, and gauge visualization. A total score was given to the participant by summing the score for each element. These scores were divided by the number of participants evaluated to give an understanding score percentage. Due to time limitations, assessing understanding was not something that was done for all participants; therefore, the n value is lower for this visualization. The scores for the trajectory visualization can be seen in the below Table 13.

Table 13: Understanding Scores for Trajectory Visualization (Trainees)

	Percent Change	*Trendline Interpretation*	*Gauge Interpretation*	*Total Score*
Understanding Score n=10	90%	90%	80%	**89%**

As indicated in Table 13, the gauge visualization was more challenging to understand than the trendline.

4.2.3.2 Themes

Table 14: Themes and subthemes for the Trajectory Visualization (Trainees)

Theme	Subtheme	Description, Quote, or Example
Visualization Usability	Interpretation of percent change	Any comment that was made by the trainees that indicated misinterpretation of the percent change in the visualization. *"It probably means that ICP has increased around 15% every hour." T2*
	Implication of percent change	Comments made by the trainees which expressed confusion about how to interpret the percent change. *"I find this visualization relative, so I don't know the actual number of ICP. I don't know what to do with the data. I know it's probably pretty bad, but I mean if someone comes from the ICP of 5 and then the other day is 10 (100%), it's probably not that bad though, but maybe had to keep in mind why it increased so high, but it's still not reached the threshold.....the relative change is a big more difficult to understand for me."T2*
	Trendline Visualization	Any comment that indicated confusion about how to interpret the trendline visualization. *"I don't understand what the graph means…It actual looks like a random line." T2*
	Gauge Visualization	Any comment that indicated confusion about how to interpret the gauge visualization. The physician commented that they were unsure what the gauge visualization represented. *T15*
Visualization Application	Alert	Any comment made by the trainees that indicated that the visualization served as an indicator, cue, or alert. *"To me, this seems analogous to the donut in that it is an alert and indicator for me to be primed that on two different time scales things are heading in the wrong direction." T4*

Visualization Usability

Visualization usability of the trajectory visualization emerged as a theme in the interviews with trainees. The four subthemes of the visualization usability from trainees were identified as the interpretation of percent change, the implication of percent change, confusion of the trendline visualization, and confusion of the gauge visualization.

Generally, the trainees were familiar with the concept of percent change and understood what this meant. However, one trainee was confused by if the hourly percent change indicated that the patient had had that increase for every hour or if it was just corresponding to the past hour.

"It probably means that ICP has increased around 15% every hour." T2

The implication of percent change on patient management and care was a common theme amongst trainees with some trainees noting that percent change may have more research value than at the bedside. The trainees noted that if there was a protocol or published research for a percent change that was deemed critical and requiring action, it would be more valuable but without this, they were unsure what they would use the information for. One trainee explained that patient treatment is based on a threshold rather than percent change and they would not know how percent change would impact their decision-making.

"I find this visualization relative, so I don't know the actual number of ICP. I don't know what to do with the data.... the relative change is a bit more difficult to understand for me." T2

The trainees also acknowledged that when the ICP is in the normal range, a higher percent change may not be as meaningful and could potentially generate false alarms if a patient's ICP goes from 5mmHg to 6.5mmHg for example. Changes that cross a threshold were regarded as having a greater impact on patient management.

The gauge and trendline representations were understood by most trainees. One trainee was unsure what the gauge visualization represented, and one trainee did not understand the trendline representation.

"I don't understand what the graph means…. It actually looks like a random line." T2

Visualization Application

The application of trajectory visualization emerged as a theme in the interviews with trainees. Four subthemes were identified in this category including training, integration with other visualizations, and alert. The integration with other visualizations was a theme that appeared across multiple visualizations; therefore, this will be discussed further in Section 4.2.5.

One trainee noted that the trajectory visualization had an application for training and more as a high-level summary. Trainees acknowledged that less experienced physicians tend to only look at the number of ICP and having this type of visualization could act as a cue to pay attention to the trend. One physician described that as they gain more experience and have a better idea of what percent change is concerning, this visualization will provide even greater value.

The trajectory visualization was regarded as an alert by several trainees, and they noted that the visualization would be especially useful when a patient is below a threshold of concern but still had a significant percent change. The trajectory visualization would cause them to be more active and monitor the patient more closely than they otherwise would.

"To me, this seems analogous to the donut in that it is an alert and indicator for me to be primed that on two different time scales things are heading in the wrong direction." T4

The trainees explained that the trajectory visualization gives a lot of information about the patient which helps determine their management strategy.

"…giving me a lot of information of what's happening now and showing me the trend of what's been happening in a very short period of time." T17

4.2.3.3 Ratings

Following the general discussion of the visualization, the trainees were asked to rate the visualization on a scale from 1 to 5 on ease of understanding and usefulness. The results for these ratings can be seen below in Table 15.

Table 15: Ease of Understanding and Usefulness Ratings for Trajectory Visualizations (Trainees)

	Mean	*Std Dev*
Ease of Understanding n=9	4.06	0.88
Usefulness n=9	3.44	1.04

4.2.4 Summation Trend Chart

4.2.4.1 Assessing Understanding

Like the other visualizations, the understanding of the participants was assessed for the summation trend chart. The participants were presented with an image of the visualization and asked to explain without any explanation, and they were asked to describe the visualization in as much detail as possible. To assess whether the participants could identify the individual variables in the summation trend chart, the participants were probed with *"Can you tell me how you understand the values for the patient's ICP, CPP, and MAP at 12:08 pm."* Understanding scores (0 or 1) were given to each element of the visualization including the colour coding of the variables, ICP, CPP, and MAP values. A total score was given to the participant by summing the score for each element. These scores were divided by the number of participants (n) evaluated to give an understanding score percentage. These scores can be seen in Table 16 below.

Table 16: Understanding Scores for Summation Trend Chart Visualization (Trainees)

	Colour Coding	*Value of ICP*	*Value of CPP*	*Value of MAP*	*Total Score*
Understanding Score n=15	100%	87%	100%	93%	**95%**

As seen in Table 16, the participant's understanding was lowest (87%) for identifying the value of ICP. Despite all participants understanding the colour coding of the variables, only 87% of participants were able to identify the ICP value and 94% of participants were able to identify the MAP value. This suggests that the chart style had an impact on the trainee's understanding of the visualization.

4.2.4.2 Themes

Table 17: Themes and subthemes for the Summation Trend Chart (Trainees)

Theme	Subtheme	Description, Quote, or Example
Visualization Usability	Challenges identifying individual variables	Visualization usability comments that revealed challenges in detecting the individual variables with the summation graph. *"It is hard to detect ICP with this graph." T8*
	Legend	Visualization usability comments about the lack of formal legend on the visualization. *"Less intuitive is you are not picking up on the colours (in the equation-legend)." T1*
Visualization Application	Relationship of variables	Any comment that mentioned that the summation trend chart has an application for visualizing the variables and the relationship of MAP, ICP, and CPP together. The physician commented that the visualization of the three variables together is useful and *"We may do things to modulate CPP and MAP as opposed to just ICP." T1*
Content Feedback	Importance of CPP Targets	Comments that mentioned the importance of CPP targets in neuro-critical care. *"CPP is what I am looking for and what I am targeting." T3*

Visualization Usability

Visualization usability of the summation trend chart emerged as a theme in the interviews with trainees. The two subthemes were identified as challenges in identifying the individual variables and the legend. The trainees expressed confusion with identifying the variable that was on the top of the summation stack, ICP. Some comments made by trainees are highlighted below:

- *"It is pretty hard to tell if the ICP has changed or not with this graph." T2*
- *"It is hard to detect ICP with this graph." T8*
- *"I find that stacked charts in general I have a hard time with…. I am not sure how useful it would for me at the bedside." T4*

In addition to these comments, 13% of users were unable to identify the value of ICP as indicated by the understanding scores in Table 16. One physician even commented that they would prefer a tabular flowsheet as the numbers are written down and the changes in each variable are clear. Many trainees expressed that they would prefer the variables be represented as three individual lines because it is easier to detect the individual variables. One trainee commented that it may be useful to include a gradient for ICP to indicate when the ICP is increasing or decreasing to make this more apparent.

"It would be nice if you could have the ICP line on the same graph rather than the difference because then I'll have to calculate it myself." T9

One physician expressed confusion around the lack of formal legend on the visualization. The physician described that although the colouring of the variables was available in the equation, this is not obvious and had the potential to confuse the user.

"…less intuitive if you are not picking up on the colours." T1

Visualization Application

Another theme that emerged in the interviews with trainees was the application of the visualizations. The two subthemes for the application visualization theme were identified as the relationship of variables and integration with other visualizations. The integration with other visualizations was a theme that appeared across multiple visualizations; therefore, this will be discussed further in Section 4.2.5.

The trainees noted that physicians are interested in looking at how a patient's ICP is changing relative to their MAP and the summation trend chart helps accomplish this. One physician explained that both ICP and CPP are important in different situations and having a visualization that displays both of these variables is valuable.

"If ICP is normal, I don't worry much about CPP, but if ICP is abnormal, then I would look at CPP to see how high I need to push the MAP up to get a good CPP." T9

The trainees appreciated the equation shown at the top of the visualization as it makes the relationship between the variables and how it applies to the graph very clear.

Content Feedback

There was one subtheme, the importance of CPP targets, that was identified under the content feedback theme. Several physicians noted that the summation trend chart should focus more on CPP and CPP targets. One trainee emphasized that they were most interested in how much time is spent in the ‘safe zone’ of CPP.

“Why are you giving me so much information minute to 30mute or values that are not useful, when what I really need in this case is to know how much time I am spending above the safe limit of CPP.” T17

The trainees explained that it would be valuable to have a target threshold for CPP and a visualization that helps them identify whether CPP is in the right range.

“CPP is what I am looking for and what I am targeting.” T3

The trainees had previously been shown the individualized thresholds visualization for ICP and one trainee noted that they would also like to see individualized thresholds for CPP.

4.2.4.3 Ratings

Following the general discussion of the visualization, the trainees were asked to rate the visualization on a scale from 1 to 5 on ease of understanding and usefulness. The results for these ratings can be seen below in Table 18.

Table 18: Ease of Understanding and Usefulness Ratings for Summation Trend Chart Visualization (Trainees)

	Mean	*Std Dev*
Ease of Understanding n=14	3.57	0.87
Usefulness n=14	3.89	1.27

4.2.5 General

4.2.5.1 Themes

Table 19: Themes and subthemes that appeared in multiple visualizations or independent of a specific individualization (Trainees)

Theme	Subtheme	Description, Quote, or Example
Impact on Management	Transitional Threshold	Any comments from the trainees that discussed how the transitional threshold would impact their management of the patient. *"…green or yellow it's the same for me…. For 18, 15, 10mmHg (ICP) it is the same treatment." T8*
General Usability	Desire for Simplicity	Comments that expressed a desire for simple design in the visualizations. The physician commented that they thought it would be more beneficial if it was simpler with less colour or fewer numbers. *T5*
	Collation of Information	Comments that emphasized the value of collating information on an integrated display. *"You want the information collated. That's what I find helpful. So, I don't want to have to look at the paper chart and see a steam of numbers and then look at this and then try and think in my head." T18*
Visualization Interaction	Time Scaling	Comments that discussed different time periods that would be important or desire to zoom in and out of the visualization. *"Ideally you would want to be able to zoom out and zoom in to the x-axis by any unit of time. Because to understand over a period of days what percentage of time someone has spent in a different ICP zone is very useful." T4*
	Target Customization	Any comments that were made that discussed the customization of ICP targets from patient to patient. *"As somebody who is a proponent of personalized medicine, I would say yes because we all know that individual patients do differ, and their physiology may differ. And so, these things may be important if tailored to the patient. So, I would say yes, that would be helpful. Because maybe a certain ICP in one patient to the next may physiologically mean different things depending on, what other information you have about the patient." T1*
	Exact Values	Comments that mentioned that knowing the exact value of a variable is beneficial either through showing them directly on the graph or graph interactions. *"I would like to have the ability to put the pointer and show me the values as I moved through the graphic." T7*

Table 19 (cont'd): Themes and subthemes that appeared in multiple visualizations or independent of a specific individualization (Trainees)

Theme	Subtheme	Description, Quote, or Example
Visualization Application	Integration with other visualizations	Any comment that mentioned that the visualization would be valuable alongside other visualizations.
	Monitoring Type	Any comments that mentioned the type of ICP monitoring that this visualization would be applicable for. The physician commented that this visualization works when an ICP signal is continuously transduced which is not always the case.
Content Feedback	ICP waveform	Comments that described the importance of ICP waveform in neuro-critical care and understanding the patient's condition. *"The waveforms have certain pathophysiological significance as well which we are not capturing in these diagrams today. So that might be an interesting compliment to be looked at from a physiological perspective." T1*
	CPP dose	Comments that indicated a desire to visualize CPP as a dose. The physician commented there were interested in knowing how much time is spent in the safe zone of CPP. *T17*
Physician Training	Autoregulation	Comments that pertained to cerebral autoregulation in physician training. *"It is very physician dependent how interested they are in autoregulation…It is something that I myself definitely don't pay as much attention to as I probably should because even though I have those three numbers (CPP, MAP, and ICP), I just don't compute them." T18*
	ICP measurement	Comments that pertained to ICP measurement in physician training. The trainee was not entirely sure about how ICP is measured. When asked if ICP is monitored the same way for a patient with an EVD vs a patient with an intraparenchymal monitor, the physician was not sure. *T11*

Impact on Management

A subtheme that was identified in the impact on management theme was the transitional threshold. Several trainees noted that if they had a patient in the transitional target range for ICP, this would not impact their management. Some other comments that were made around the transitional target are described below:

- *"Green or yellow, it's the same for me…For 18, 15, 10mmHg (ICP), it is the same treatment."* The physician explained that they were unsure of the value of having a transitional target. They noted that if a patient had an ICP that went from 8-15mmHg (normal-transitional), they would not do anything because it is still below the high ICP range. *T8*

- One physician explained that they don't care about changes from 17-18mmHg (within the same intensity range, transitional range) however, they do care about changes into the high ICP range. *T6*

Although the trainees acknowledged that they may pay attention and try and lower the patient's ICP if it is in the transitional range, they care most about changes into the high ICP range.

General Usability

A desire for simplicity and collation of information were two subthemes that appeared across multiple visualizations. The trainees tended to appreciate simple visualizations that presented data in its raw form. Two trainees compared the ICP dose bar chart to the individualized threshold visualization:

- The physician explained that they preferred the individualized threshold visualization to the ICP dose visualizations because it showed the exact values of ICP making it more obvious and easier to interpret. *T18*

- The trainee commented that the individualized threshold visualization is *"the most informative and least distracting." T3*

One trainee explained that the individualized threshold could benefit from an even simpler design.

"I can see the curve, why would I have a need for the green, red, and yellow. I know what the thresholds are so why should I have these colours." T6

One trainee commented that the ICP dose bar chart would be more beneficial if it was simpler with fewer colours and numbers. These comments all indicate a desire for simple visualizations.

The collation of information subtheme was also identified in comments for the ICP dose visualization and individualized threshold visualization. The trainees appreciated that the visualizations integrated multiple pieces of information and summarized information making it easier to identify trends and come up with a management strategy.

"(ICP dose bar graph) You want the information collated. That's what I find helpful. So, I don't want to have to look at the paper chart and see a stream of numbers and then look at this and then try and think in my head." T18

"(ICP dose bar graph) It is very useful. It triggers the alarm in your head in multiple ways. Not just looking at the ICP number but the amount of time spent which is a huge concept." T4

The trainees appreciated having the information on one screen as this takes away the mental effort required to compare numbers on multiple different screens and data sources. One trainee explained that their current process for comparing ICP to targets is very active.

"The current way of doing it is very active meaning that I would have to look at the paper (order sheet) and I would have to look at the patient's ICP and then I would have to synthesize the two. This (individualized threshold) takes that work away and all I have to think about is whether they are in the zone or not, so it takes some of that mental load away." T4

Visualization Interaction

In the visualization interaction category, the subthemes time scaling, target customization, and exact values appeared in multiple visualizations. The trainees believed that the time frames represented in the visualizations made sense as a starting point, but they would also appreciate the ability to zoom in and out of the visualizations and customize the time frame depending on their patient.

"(ICP dose bar graph) Ideally you would want to be able to zoom out and zoom in to the x-axis by any unit of time. Because to understand over a period of days what percentage of time someone has spent in a different ICP zone is very useful…If a patient's condition changes, it usually changes on an hour or minute-by-minute basis and so I would want to be able to zoom in even closer." T4

The trainees explained that one time frame will not be universally useful, and it would be important to be able to customize the time frame for different situations.

Target customization for ICP intensity ranges was also acknowledged as a valuable addition to an interface providing the targets are clearly displayed and the rationale behind the targets is understood.

"As somebody who is a proponent of personalized medicine, I would say yes, because we all know that individual patients do differ and their physiology may differ. And so, these things may be important if tailored to a patient…. Because maybe a certain ICP in one patient to the next may physiologically mean different things, depending on, what other information you have about the patient." T1

"If you adjust it, it needs to be shown somewhere and everybody needs to know the rationale behind why we adjust it." T9

Understanding the exact values of variables was a common subtheme in the discussion with trainees. In all the visualizations, the trainees appreciated having an exact number to communicate whether it be an ICP burden percent or the exact value of ICP. Several trainees noted the desire to be able to hover their mouse over the visualization to show them the exact values rather than having to look at the y-axis. On the trajectory visualization, trainees commented that they would appreciate having the minimum and maximum values of ICP on the visualization. The summation trend chart was another visualization in which the trainees noted that they would like to see the exact values when they hover over the graph. The challenges of identifying individual variables in the summation trend chart may also contribute to this comment.

"(Summation Trend Chart) I would like to have the ability to put the pointer and show me the values as I moved through the graphic." T7

Visualization Application

In the visualization application category, integration with other visualizations, and type of monitoring were two subthemes that emerged. The trainees noted that many of the visualizations would provide even greater value if they were integrated with other visualizations. This was especially the case for the trajectory visualization. Several trainees noted that the trajectory visualization may not be very useful on its own but could provide greater value if it was shown alongside other visualizations or used as a summary. The summation trend chart was regarded as different and complimentary from the other visualizations that focused on ICP.

The type of monitoring was brought up as a consideration for the visualizations and one trainee explained that the dose visualization would rely on accurate ICP readings and continuous ICP monitoring. They explained that when the ICP is monitored through an EVD, there will be times when the ICP signal is not transduced thereby making the dose visualization challenging to create. This comment applies to other visualizations as well and is a consideration for future work.

Content Feedback

The importance of the ICP waveform and visualizing CPP as a dose were two subthemes in the content feedback category. A few trainees mentioned that they would like to see a visualization that shows them waveform information and they further described that the waveform peaks (P1/P2/P3) can be used to help predict a high ICP. Another physician mentioned that they would like to be able to see if there are Lundberg A waves which can be an indicator of impending herniation.

"The waveforms have a certain pathophysiological significance as well which we are not capturing in these diagrams today. So that might be an interesting compliment to be looked at from a physiological perspective." T1

The importance of CPP targets was identified as a subtheme in the summation trend chart results. One trainee further emphasized the importance of CPP and targets by explaining that they would like to know how much time is spent in the safe zone of CPP and that it would be interesting to explore a CPP dose visualization in addition to the ICP dose visualizations.

Physician Training

Physician training emerged as a theme in the interviews with trainees, with trainees commenting that autoregulation and how ICP is measured is not something they think about. One physician explained that a patient's autoregulatory status is not something they think about in their day to day. Another trainee explained that some staff physicians focus more on autoregulation than others, but as a trainee, autoregulation is not something that is embedded in their decision-making. Although the trainees had awareness of the steps that they would need to take to check autoregulatory status such as driving up the blood pressure to see how the ICP responds, this was not something that they would perform unless asked by a staff physician.

"It is very (staff) physician dependent how interested they are in autoregulation…. It is something that I myself definitely don't pay as much attention to as I probably should because even though I have those three numbers (ICP, CPP, and MAP), I just don't compute them." T18

The trainee commented that autoregulation is not something that they have grasped in their training in critical care and there is no formal documentation of a patient's autoregulatory status.

Another subtheme that arose was ICP measurement. One trainee explained that they were not sure how ICP is measured and what the value of ICP on a monitoring screen represents. Additionally, the trainee was unaware of the differences between ICP monitoring with an EVD or intraparenchymal monitor.

4.2.6 Overall Prioritization

At the end of each interview, the participants were asked to choose which visualizations they would appreciate most on a bedside physiologic monitor. They were told that they could choose none or as many as they believed would provide value. Since not all visualizations were shown to every participant, the prioritization was given a percentage score based on how many participants selected the visualization out of the total number that was asked for prioritization of the visualization. For example, a total of 17 participants were shown the ICP dose- bar chart visualization and asked for prioritization, and of those 17 participants, 9 participants said they would appreciate the visualization on a bedside physiologic monitor. Therefore, this visualization is given a prioritization score of 53% or 9/17. This represents the percentage of trainees that selected the visualization on a bedside display. The prioritization scores can be seen below in Table 20.

Table 20: Overall prioritization scores for all visualizations (trainees)

	# Participants Evaluated	*# Participants Prioritized*	*Prioritization Score*
ICP Dose-Bar Chart	17	9	**53%**
ICP Dose-Donut Chart	12	4	**33%**
Individualized Thresholds	17	13	**76%**
Trajectory	14	6	**43%**
*Summation Trend Chart**	17	12	**71%**

** Prioritization scores include any version of this visualization. Some participants noted they would appreciate this visualization as a line graph rather than a summation trend chart*

As Table 20 shows, the participants appreciated the individualized thresholds visualization the most followed by the summation trend chart and ICP Dose-bar chart.

4.3 Discussion

This study investigated trainee physicians' comprehension and perceptions of the EID visualizations for use on a bedside physiologic monitor. The main goal of the interviews with trainees was to understand usability concerns and gather general feedback on the visualizations. The visualizations were analyzed individually but also globally to understand themes that were consistent across multiple visualizations. The subthemes that appeared across multiple visualizations include the desire for simplicity (general usability), collation of information (general usability), time scaling (visualization interaction), target customization (visualization interaction), exact values (visualization interaction), integration with other visualizations (visualization application), monitoring type (visualization application), ICP waveform (content feedback), CPP dose (content feedback), autoregulation (training), and ICP measurement (training).

Any comments made that indicated user confusion in the visualizations (visualization usability) needed to be addressed in the final design of the interface and even if a comment was only mentioned one time, this was included as a subtheme of visualization usability. These comments highlight the importance of usability testing in the early stages of design. Despite the trainees being confused about various aspects of the visualizations, when the visualizations were described to them, they did not express further confusion. This suggests that interface training will play an integral role in addressing usability and confusion. Below, Table 21 describes the visualization usability themes and the potential impact they had on the final design described in Chapter 6. The potential impacts were re-evaluated after the discussions with staff physicians and final design impacts were determined in Section 5.3.1.

Table 21: Visualization usability themes and potential impacts on design (trainees)

Visualization	Visualization Usability	Potential Impact
ICP Dose	Interpretation of ICP burdens and percentages	- Re-evaluate after interviews with staff physicians. - Include a description of the visualization with an example in the interface training video.
	Wording of y-axis	- Discussion with staff physicians around the wording of the y-axis. - Include a description of the visualization with an example in the interface training video.
	Two axes in context with graph description	- Re-evaluate after interviews with staff physicians. - Allow users the ability to toggle the multiple y axes to eliminate the confusion of multiple axes. - Include a description of the visualization with an example in the interface training video.
Individualized Threshold	Detection of threshold change	- Include the current ICP thresholds next to the visualization so users are aware of the current targets and when they change. - Include a description of the visualization with an example in the interface training video.
	Interpretation of the colours of ICP intensity ranges	- Consider what is being displayed together on the interface. For example, if colours are similar in two visualizations but represent different things, this may confuse users. - Include a description of the visualization with an example in the interface training video.
Trajectory	Interpretation of the percent change	- Include a description of the visualization with an example in the interface training video.
	Implication of the percent change	- Consider what is being displayed together on the interface. For example, a percent change on its own may be confusing but displaying this alongside other information may provide context. - Include a description of the visualization with an example in the interface training video.
	Trendline visualization	- Re-evaluate after interviews with staff physicians. - Include a description of the visualization with an example in the interface training video.
	Gauge visualization	- Re-evaluate after interviews with staff physicians. - Include a description of the visualization with an example in the interface training video.
Summation Trend Chart	Challenges identifying individual variables	- Re-evaluate after interviews with staff physicians. - Give users visualization interaction to show the exact values or toggles on the variables so they can look at the variables independently. - Include a description of the visualization with an example in the interface training video.
	Legend	- Include a standard legend in addition to the equation to eliminate confusion. - Include a description of the visualization with an example in the interface training video.

Compared to the current interfaces and data records that many of the trainees were familiar with, the trainees noted that the *collation of information* in the visualizations was extremely valuable. The interviews revealed that any visualizations that allowed them to look at multiple variables or pieces of information together were viewed as an improvement from the current interface that requires switching between multiple screens and sometimes even integrating paper flowsheets with the bedside monitor. This integration of information is taxing and requires a high mental workload. Previous research conducted on advanced bedside physiologic monitors have shown that the performance of the healthcare team is improved with the integration of information from several devices onto a single screen (*collation of information*), providing the information is not overwhelming (*desire for simplicity*) or the display is not drastically different from standard monitors (*familiarity*) (Gorges et al., 2011; Koch et al., 2012).

Many of the trainees had a numerical, threshold-based approach to ICP management. This was highlighted by the comments from trainees on the impact that a *transitional threshold* for ICP would have on their management strategy and the implication of percent change in ICP. There are no guidelines for transitional targets for ICP or a percentage change that is considered ‘malignant’ therefore, the trainees were unsure that these pieces of information would impact their strategies.

Generally, the trainees appreciated the simple visualizations (*desire for simplicity*) that displayed data in its raw form such as the individualized threshold visualization and the summation trend chart visualization (as described in the prioritization Table 20). Both these visualizations did not have any calculated parameters such as percent time in a range or percent change in a variable and therefore were regarded as easier to understand than the ICP dose visualization (bar chart). However, ecological interfaces are not designed to be easy but rather help trainees develop more sophisticated mental models and think of the relationships between variables that otherwise may be challenging (Burns & Hajdukiewicz, 2004). Although the ease of understanding ratings and understanding scores suggest that the trainees had more challenges understanding the ICP dose visualization compared to the others, 53% of participants indicated that they would like this visualization available to them on a bedside display. After the explanation of the visualizations, trainees had a greater appreciation and there were even times that they chose the visualization in the final prioritization despite having initial challenges with understanding. This suggests that although trainees may not have initially found a visualization intuitive or easy to use, they still saw the value in the visualization on a bedside physiologic monitor once they understood the visualization. The prioritization scores indicate that users have different preferences and that every visualization was regarded as valuable by multiple trainees interviewed. The trainees also appreciated that many of the visualizations were *complimentary* and had greater application if they were *integrated with other visualizations.*

The trainees expressed a desire to be able to customize and interact with the visualization with *time-scaling*, *target customization*, and interactions that allow them to see the *exact value* of a variable. The different preferences of trainees indicate the importance of having some level of customization to allow users to adjust the interface. However, there are also challenges with this in a healthcare setting where multiple healthcare providers are using the bedside physiologic monitor and have different needs. Therefore, there must be a balance between customization and standardization so that each user can easily adjust the interface to their preferences.

Autoregulation plays a key role in the regulation of brain blood flow and for TBI patients, it is a predictor for worse outcomes. Understanding a patient's autoregulatory status can aid in prognostication and contribute to individualizing patient thresholds for ICP and CPP (Svendung Wettervik et al., 2022). Despite the importance of autoregulation, discussions with trainees revealed that autoregulation was not something that they have a handle on from their training (*autoregulation)*. Although they were aware of certain methods to investigate a patient's status, this was not something that they would do unless directly asked by a staff physician. This suggests that training and interface modifications that highlight the importance of autoregulation will have a positive impact on patient outcomes. This also highlights that the design of the interface to support expertise development must be done with expert feedback as trainees '*don't know what they don't know'* and may not even realize what is important in a display.

4.4 Conclusions

The preliminary usability assessment with trainees allowed us to understand elements of the visualizations that trainees found confusing before discussing with the staff physicians to further refine the designs. Visualization usability themes from the trainees were brought up in discussions with staff physicians to discuss potential solutions and design iterations. Overall, the trainees had positive impressions of the visualizations and all trainees prioritized multiple visualizations as an addition to the bedside physiologic monitor. The next chapter presents the results from the feedback sessions with staff physicians as well as the final design impacts from both rounds of interviews. Limitations and recommendations for future work are presented for both groups in Chapter 7.

Chapter 5
Design Refinement and Feedback Elicitation

The interview results with the trainees (outlined in Chapter 4 Preliminary Usability Assessment) aimed to identify usability concerns with the version 2 visualizations and resulted in several impacts on the design. The themes from the interviews with trainees were also re-evaluated after the interviews with experts to ensure that both comments are captured in the final design. This next chapter summarizes how the designs were iterated and refined through feedback sessions with expert physicians.

5.1 Method

The interviews with the staff physicians were conducted to validate the version 2 visualizations, discuss neuro-critical care concepts and variables that are important to optimize patient outcomes, as well as discuss improvements and modifications to the visualizations. The design process of the visualizations was iterative and as more feedback was gathered, design iterations were generated, and new iterations were presented in subsequent interviews.

5.1.1 Semi-Structured Interviews

The feedback from the expert physicians was elicited through qualitative semi-structured interviews. The feedback was collected in one-on-one interviews to avoid the experts being biased and influenced by one another. The study received ethics approval through the University of Waterloo Research Ethics Board. Like the interviews with trainees outlined in Chapter 4, the interviews with staff physicians were 60 min in total, and 30 min were allotted to the visualization discussion which was the second part of a longer interview including a discussion of expertise in neuro-critical care. The overall study protocol is described below in Figure 20.

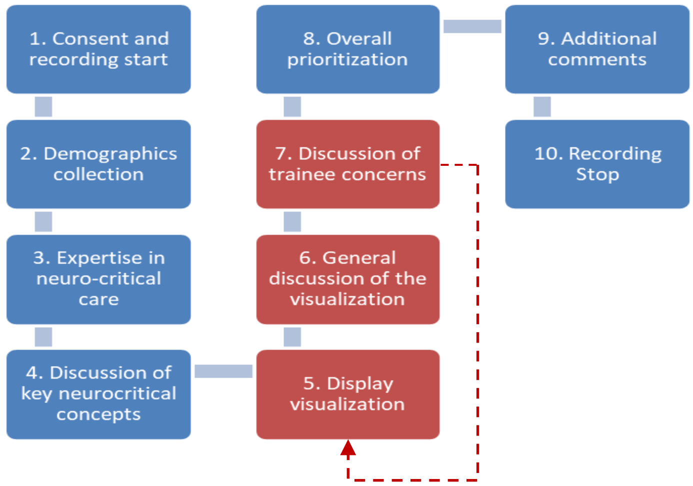


Figure 20: Interview protocol for staff physicians

The semi-structured interviews were modular, and the visualization section of the interview consisted of six main sections (described by steps 4 through 10 in Figure 20). For each visualization, steps 5-7 were repeated. Like the interviews with trainees, the order that the visualizations were presented was the same for each participant starting with the ICP dose visualizations and ending with the summation trend chart. For the general discussion of the visualizations, the probing questions with the staff physicians were the same as the trainees. We did not assess the understanding of the staff physicians. Another difference from the interviews with trainees was at the end of the general discussion, we raised concerns that the trainees identified with the visualizations. This was done to facilitate a discussion on how these concerns could be addressed in the final interface design. The main sections of the visualization section of the interview are described in Table 22.

Table 22: Description of key steps in the visualization section of the semi-structured interviews with experts

#	Step Name	Description
4	Discussion of key neurophysiologic concepts	Experts were presented with three concepts of neuro-critical care and asked to provide feedback if anything was missing or not captured in the concepts listed.
5	Display Visualization	The experts were presented with the static visualization and explained the visualization and the goal of the visualization to the experts.
6	General discussion of the visualization	For each visualization, a general discussion of the visualization took place. Some questions that were asked include. To facilitate discussion, probes were asked of the experts such as *"When you are looking at a patient's ICP, what time frame is most valuable to you?"* or *"Does the percent change of a patient's ICP provide any value to you as a clinician?"* or *"What vital information would you be interested in looking at first for a neuro-critical care patient?"*
7	Discussion of trainee concerns	For each visualization, a discussion of the trainee's concerns took place.
10	Overall Prioritization	At the end of the interviews, the experts were shown all the visualizations again and asked to prioritize which visualization(s) they would appreciate most on a bedside physiologic monitor. It was emphasized that they could choose multiple or none depending on their preferences.

The interviews were conducted virtually over Microsoft teams with two interviewers (KS and EU) on the call and one interviewer asking the questions. The participants were given consent and demographic questions before beginning the session. Refer to Appendix A for the recruitment materials, information letter, and remuneration letter and Appendix B for the questions posed in semi-structured interviews.

5.1.1.1 Participants

Participants were recruited through subject matter expert and critical care physician, Dr. Victoria McCredie. The participants were sent an invitation to sign up for the study which included the goal of the study, remuneration amount, study requirements, and a Calendly link to sign up for a 60 min interview. A total of 18 participants were interviewed as part of this study. All the participants were current experts (staff physicians) in critical care. The table below shows the demographics of the 18 participants interviewed. All staff physicians were currently working in a university hospital (2 also worked in a community hospital) and had residents training at the hospital. Years of experience represent the number of years in independent practice.

Table 23: Demographics of staff physicians

S#	Age	Gender	Years' Experience	Specialty	Subspecialty	Country
S1	39	M	4.5	Internal Med	Respirology Critical Care	US
S2	58	M	26	Neurology* Vascular Neurology*	Neuro-critical Care*	US
S3	48	M	17	Internal Med	Critical Care Neuro-critical Care	CA
S4	54	M	23	Internal Med	Critical Care	CA
S5	55	M	18	Anesthesia*	Critical Care Neuro-critical Care	CA
S6	51	M	20	Anesthesia	Critical Care	CA
S7	44	F	15	Internal Med	Critical Care	CA
S8	45	M	8	Internal Med* Emergency*	Neuro-critical Care	CA
S9	39	M	8	Internal Med	Critical Care	CA
S10	46	F	15	Neurology* Vascular Neurology*	Neuro-critical Care*	US
S11	60	M	32	Anesthesia	Neuro-critical Care	CA
S12	63	F	28	Neurology*	Critical Care*	US
S13	50	M	19	Internal Med	Critical Care	CA
S14	56	M	23	Internal Med	Critical Care Neuro-critical Care Epidemiology	CA
S15	64	M	30	Pediatric Med	Critical Care	CA
S16	36	F	5.5	Neurology	Critical Care Neuro-critical Care	CA
S17	41	F	9.5	Internal Med	Critical Care	CA
S18	40	M	7	Neurology* Neurophysiology*	Critical Care* Neuro-critical Care*	US

* indicates certification received in another country.

5.1.1.2 Analysis

After the interviews were conducted, the Microsoft teams recording were transcribed using the Microsoft team's transcription software. The interviews were summarized, and any relevant quotes were included in this summary which was sent back to the participant for review. The participant was asked to review the summary and comment with any changes if applicable. The recordings, transcripts, and summaries are stored on a hard drive owned by the authors (KS and EU) and used later in data analysis.

The interviews were analyzed using inductive thematic analysis. The same process described in Section 4.1.1.2 for the interviews with trainees was used to analyze the interviews with staff physicians. The themes and subthemes that were identified in the data from staff physicians overlapped with the trainees. For a final analysis step, the themes and subthemes from the trainees were examined together with the staff physicians to determine the final impact on design.

5.2 Results

The interviews with staff physicians were coded by each visualization and globally (evaluating all visualizations together). Table 24 includes the themes and subthemes that emerged for each visualization. The bolded subthemes in Table 24 appear across multiple visualizations and will be discussed in Section 5.2.5. The subthemes with an asterisk were themes that were also included in the interviews with trainees.

Table 24: Staff physician themes for each visualization. Starred subthemes appear as trainee subthemes and bolded themes appear across multiple visualizations.

Visualization	Theme	Subtheme
ICP Dose	Visualization/General Usability	- Desire for simplicity* - Differentiation of higher ICP values - Collation of Information* - **Intuitiveness*** - Two axes in context with graph description* - The wording of the y-axis*
	Visualization Application	- Trend* - Complimentary* - **Different Users**
	Distribution of ICP values	- Average* - Fluctuations in ICP* - Duration of ICP Events
	Visualization Interaction	- **Time Scaling*** - **Target Customization***
Individualized Thresholds	Content Feedback	- **Annotations***
	Design Preferences	- Consider what is being displayed together - The area under the curve - **Salience*** - Consistency - Coloured line
	Visualization Application	- **Different users** - **Integration with other visualizations***
	Visualization Interaction	- **Target Customization*** - **Exact Values***
Trajectory	Visualization/General Usability	- Interpretation of percent change* - Implication of percent change* - Redundant
	Visualization Application	- **Alert*** - Presence of absence of evidence - Changes above threshold - **Integration with other visualizations*** - Promotes looking beyond a threshold
	Visualization Interaction	- **Exact Values*** - **Time Scaling***

Table 24 (cont'd): Staff physician themes for each visualization. Starred subthemes appear as trainee subthemes and bolded themes appear across multiple visualizations

Visualization	Theme	Subtheme
Summation Trend Chart	Content Feedback	- Importance of CPP Targets*
	Visualization/General Usability	- Challenges identifying individual variables*
	Visualization Application	- Autoregulation - Relationship of variables*
	Visualization Interaction	- **Exact Values***
	Design Preferences	- Line graph - Advanced Summation trend chart - Summation trend chart

5.2.1 ICP Dose

The ICP dose visualization themes and subthemes are presented in the following sections.

5.2.1.1 Themes

Table 25: Staff physician themes for ICP dose. Starred subthemes appear as trainee subthemes.

Theme	Subtheme	Description, Quote, or Example
Visualization Application	Trend*	Any comment that discussed the importance of the patient's trend in visualizations. *"I like the bar chart because it gives you a sense of how things are progressing which is really, I think helpful. The longitudinal progression of stuff is not easy to interpret just from the raw data." S18*
	Complimentary*	Comments that were made about the bar chart and the donut chart having different applications, but both providing value. *"…as someone is transitioning into that kind of defervescence phase, the donut would be exceedingly helpful."S16*
Visualization/ General Usability	Desire for simplicity*	Any comments made by the staff physicians highlighted a desire for a simple design. *"In general, the more simplistic the better but it also depends on what the goal is." S17*
	Collation of Information*	Comments that acknowledged that looking at different information together provided value. The physician commented that the representation of ICP dose and duration of ICP events was valuable.
	Differentiation of higher ICP values	Comments that highlighted that the visualization does not discriminate between moderately high and very high ICP values. *"The patients I am concerned about are above 15mmHg the whole time…. I don't know if this graph is going to be very discriminatory." S7*
	Two axes in context with graph description*	Any comments that mentioned the two y-axes as they pertained to the stacking order of ICP intensities. The physician commented that it makes sense to include high ICP on the bottom of the stack to give the impression that green (or normal ICP) is being crowded out. *S10*
	The wording of the y-axis*	Comments that discussed the wording of the y-axis, any confusion, and preferences. *"…not clear what secondary insult dose means and what intracranial pressure time burden is." S17*
Distribution of ICP Values	Average*	The average subtheme included comments made about the utility of showing an average value of ICP. *"Average is more likely to hinder things than help." S4*
	Duration of ICP events	Comments that mentioned the importance of the duration of ICP events.
	Fluctuations in ICP*	Any comments that were made about the fluctuations in ICP values and desire to show a range and peak values. *"The variability is also extremely important to me." S8*

Visualization Application

One theme that emerged in the interviews with staff physicians was the application of the visualizations. The three subthemes for the application visualization theme were identified as a trend, complimentary, and different users. The subthemes trend and complimentary both appeared in interviews with trainees as well and the different user subthemes appeared across multiple visualizations and will be discussed in Section 5.2.5.

The experts acknowledged that although simpler and easier to understand, the bar chart representation of the ICP dose is more informative as it indicates when the patient had high ICP over the time frame. The bar chart clearly shows a trend and gives the physician information on when the patient's ICP was high and if the patient is getting better, worse, or staying the same.

"I think the hour-to-hour is more important and informative." S7

Despite being more informative, the staff physicians believed there was an application in both visualizations, and they have value at different stages in the disease process. One physician noted that the donut visualization would be useful to help understand when the patient no longer requires an ICP monitor.

"… as someone is transitioning into that kind of defervescence phase, the donut would be exceedingly helpful." S16

The staff physicians commented that the donut chart would be mainly used as a summary and the bar chart would be used during the investigation of a patient. There was discussion around the importance of having different representations as there will be differences in how healthcare team members digest information.

"Different levels and types of providers may benefit from different types of presented information." S2

Usability

Any comments that were made around the usability of the visualizations were grouped into the usability theme. The subthemes in this category were identified as differentiation of higher ICP values, desire for simplicity, intuitiveness, collation of information, two axes in context with graph description, and the wording of the y-axis. The only subtheme that did not appear in the interviews with trainees was the differentiation of higher ICP values.

The colour coding of the ICP ranges was described as easy to understand and familiar, thereby helping physicians easily identify a patient's trend. There was some concern around the inability of the current ranges to differentiate a patient who has an ICP of 35mmHg, or an ICP of 22mmHg. For example, on the bar chart with the standard ranges for ICP, a patient who spends 1 hour above an ICP of 35mmHg will show as red or high ICP for that entire bar. Similarly, a patient who spends 1 hour above an ICP of 22mmHg but less than 24mmHg, will appear the same despite having a significantly higher ICP.

"I don't know if this graph is going to be very discriminatory." S7

A suggestion raised to help distinguish high ICP levels was to introduce a fourth darker red level of ICP for values greater than 25-30mmHg. The staff physicians generally noted that there needs to be a balance between simplicity and quantity of data and one staff physician explained that the current dose visualizations have kept it simple and not overwhelming or overburdensome for the user. There was one physician that noted that having an additional colour of ICP intensity may have the potential to confuse trainees.

"I think visually adding another colour would be potentially confusing to more junior people that are managing these patients." S16

Generally, the staff physicians appreciated the colour coding of the visualization and commented that it was intuitive and easy to understand. One physician explained that traffic light colouring is international, and this helps with '*one glance potential'* of the visualization. However, one staff physician expressed concern about the intuitiveness of the bar chart visualization explaining that is unfamiliar and confusing.

"It is weird to have something on the y-axis that is a summary of something on the x-axis." S17

The staff physicians believed that the dose visualizations effectively represented the dose concept and helped show that ICP management is not only about the ICP values but also how long a patient remains at an ICP value (duration of events).

The multiple axes and the stacking order of ICP intensities on the bar graph had inconsistent feedback from staff physicians. One staff physician noted that it made sense to reverse the order or normal, transitional, and high ICP and have high ICP at the top of the stack to align with the higher ICP values on the right y-axis reading the average. However, another staff physician noted that it is better to have the high ICP on the bottom of the stack (as represented) because this way it shows that the normal ICP is being *"crowded out"* by higher ICP value. Additionally, it is easier to see the increase in proportions that are at the bottom of the stack.

The wording of the left y-axis was a general discussion point with staff physicians. The original wording of the y-axis with the interviews with trainees was 'Percent time at ICP Intensity' however, several trainees expressed confusion with this title. Other axis titles were explored including ICP Burden (%), ICP Burden (% of time), and ICP Time-Burden (%). The staff physicians generally appreciated the title ICP Time-Burden (%) and found it to be the most representative title for the axis. However, one staff physician noted that trainees may not know what burden means and this would need to be explained. One staff physician that did not have expertise in neuro-critical care noted confusion with the ICP dose visualization and was not sure what the ICP time burden represented.

"Not clear what secondary insult dose means and what ICP Time Burden is." S17

Distribution of ICP Values

Consistent with the interviews with trainees, the staff physicians commented on the distribution of ICP values with three subthemes in this category: average, fluctuations in ICP, and duration of ICP events. The duration of ICP events was the only theme that did not appear in the trainee interviews.

Generally, the staff physicians appreciated the average ICP line and value on the dose visualizations and explained that the average line on the bar graph helps show the trend. However, there was concern about the risk associated with only showing the average, as an average does not display the nuances in ICP as the raw data does. For example, a patient with an average ICP of 19mmHg may initially not cause a physician to be alarmed, but what is more important is that the patient spent 50% of the hour at an ICP higher than 20mmHg.

The staff physicians explained that in addition to the average ICP, the variability of ICP is important to understand. The average ICP can help identify the overall trend of the ICP values, but it is more often the peak value that they are interested in and the fluctuations in ICP.

"If the ICP was oscillating between 2 and 40mmHg because they (the patient) were getting plateau waves, your mean might be 20 but actually the important thing is that it was up at 40mmHg." S5

Another subtheme that was identified was the duration of ICP events and how many events take place. One physician explained that they are interested in the maximum value of ICP events but also how many ICP events or spikes take place in an hour. Another staff physician explained that there may be instances where a patient is coughing which will cause the ICP to spike to a high value but what they are most interested in are the sustained peaks and maximum values.

5.2.2 Individualized Thresholds

The individualized threshold visualization themes and subthemes are presented in the following sections.

5.2.2.1 Themes

Table 26: Staff physician themes for Individualized threshold visualization. Starred subthemes appear as trainee subthemes.

Theme	Subtheme	Description, Quote, or Example
Content Feedback	Annotations*	Any comment made about the value of annotating events such as medication administered or other treatments. *"Important to help visualize the effect of our intervention and confirm the impression which sometimes may be wrong." S7*
Design Preferences	Consider what is being displayed together	Comments that acknowledged that preference of design would depend on what else is being displayed. The physician commented that their preference depends on what else is being displayed. *S5*
	The area under the curve	Comments from the physician that described a new visualization type where the area under the curve was coloured according to the ICP range. The physician commented that their preference would be for an area under the curve representation where the total area would correspond to which range the ICP is in. *S3*
	Salience*	Comments made around a preference for a certain design based on the salience of that design. The physician commented that it is important to keep the visualization quiet until there is a problem. *S3*
	Consistency	Any comments that acknowledged consistency between the designs and its importance. The physician commented that it is useful to colour the same as the bar chart. *S16*
	Coloured Line	Comments from the physician that described a new visualization type where the ICP line was coloured. The physician described a visualization in which the line is coloured by the ICP intensity range rather than an area under the curve representation. *S5*

Content Feedback

Consistent with the interviews with trainees, the idea of annotations to understand a patient's response to treatment emerged as a subtheme. A challenge that the staff physicians noted with neuro-critical care was understanding if an intervention is effective and how the patient is responding to different treatments. The staff physicians believed that the ability to track and filter annotations visually such as medication, sedation, and patient position on the individualized threshold visualization would provide context for the ICP values and help understand a patient's response to treatment. One physician explained that with current representations, it can be challenging to understand the effect of interventions and it would be valuable to help confirm a physician's hypothesis with real data.

"(Annotations are) Important to help visualize the effect of our intervention and confirm the impression which sometimes may be wrong." S7

Although the addition of annotations was regarded as valuable in theory, one expert noted that this would be challenging to implement in practice. The staff physician explained that in the center they currently work at, there is the ability to track annotations on the bedside software, but the manual entry is cumbersome for the nursing team that must enter it.

"I think asking manual input of these things (annotations) *so far has been a failure." S2*

The staff physician explained that the value of annotations will only be realized if the process of entering the annotations is easier to use or better yet, automated.

Design Preferences

The four subthemes in the design preferences category include consistency, salience, coloured line, the area under the curve, and considering what is being displayed together. The experts appreciated that the colour coding of the individualized threshold visualization was consistent with the ICP dose bar and donut chart. As different feedback was received from staff physicians and trainees, the designs were iterated, and the various visual representations were discussed (see Figure 21).

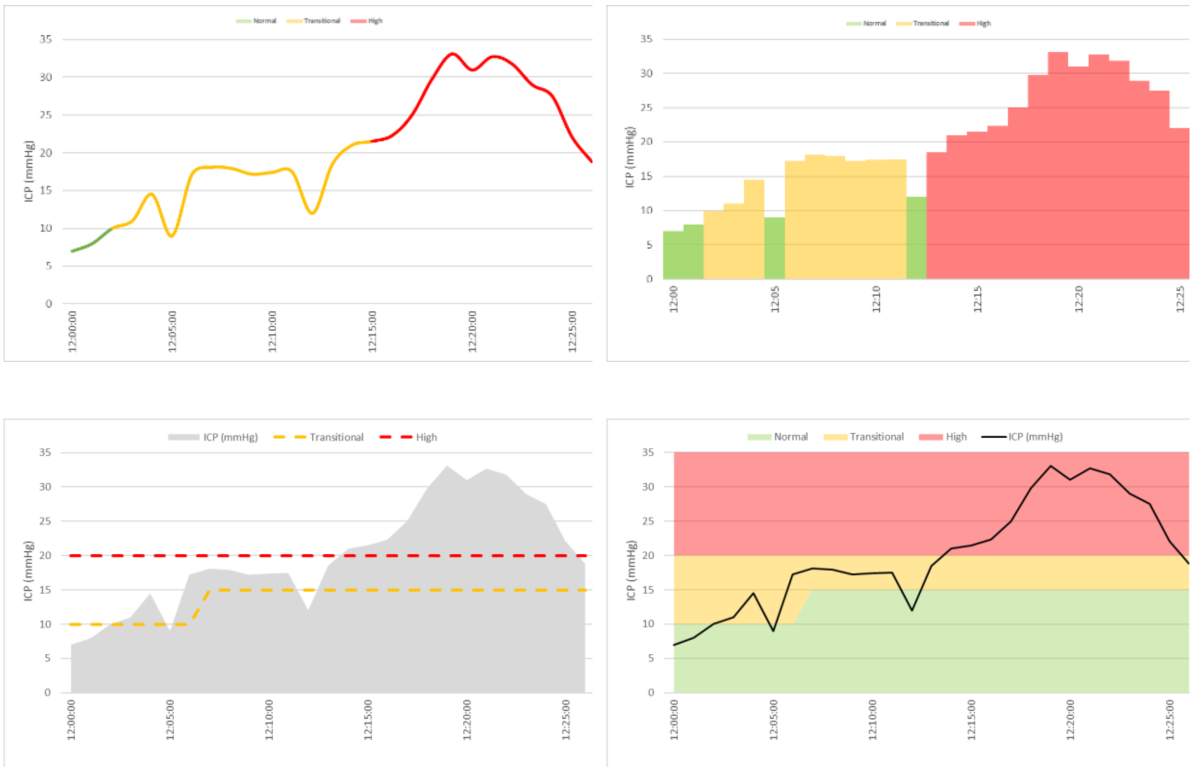


Figure 21: Various designs of the individualized threshold visualization

Despite the discussion of different visual representations with several experts, the staff physicians noted that the various visualizations are all easy to understand and it will be important to consider what is being displayed together on the interface and evaluate with real data. One physician commented that the dashed line (bottom left) with target representation is less likely to be confused with the ICP dose graph and it is important that the visualizations are distinct from one another as they are displaying different information. There was also a discussion with one physician about keeping the visualization muted unless the patient's ICP is elevated and then alerts the user with a more salient visual. For example, for ICP values in the normal range, the visualization would remain neutral and as the patient climbs to a more concerning ICP, the visualization changes colour to yellow and then red to bring the user’s (physician) attention that there is a problem that needs to be addressed.

5.2.3 Trajectory

The trajectory visualization themes and subthemes are presented in the following sections.

5.2.3.1 Themes

Table 27: Staff physician themes for trajectory. Starred subthemes appear as trainee subthemes.

Theme	Subtheme	Description, Quote, or Example
Usability	Interpretation of percent change*	Any comments that raised concern about how the percent change in ICP would be interpreted. *"I really struggle with percent change because the phenomenon is not linear and there is an implicit sort of implication in the concept that your denominator is either constant or is really relevant because it is a fraction." S11*
	Redundant	Comments that mentioned that the visualization would not be required as the information is captured in other visualizations. *"Any trend I am looking for, you would see in the timeline."* S10
Visualization Application	Alert*	Any comments that discussed the application as an alert or warning. *"(the goal is to…) Increase our ability to identify trends and synthesize information and decrease our cognitive load and everything is flashing, it's a bit of a problem." S3*
	Presence of absence of evidence	Any comments made about the evidence of percent change in ICP and whether there is research to suggest that a certain percent change is meaningful. *"I can understand why a trainee may not care (referencing percent change visualization), but for me, I care. I may not know what to do with it, but I am going to put pressure on science to tell me what to do with it." S8*
	Changes above threshold	Comments that mentioned that changes above a certain threshold are more meaningful. *"A lot of neuro is threshold driven, not that we always know what if the threshold for that specific patient…. So, I think a lot of this will end up being dismissed at the end until you maybe get close to the borderline values where you're worried." S7*
	Promotes looking beyond a threshold	Any comments that acknowledged the visualization's ability to promote physicians to look beyond a threshold-based approach. *"...people are mired in their old threshold-based ways." S2*

Usability

General comments were made around the usability of the visualization and the main subthemes were identified as the interpretation of percent change and redundancy. The interpretation of percent change was also a subtheme that emerged in the interviews with trainees.

Some of the staff physicians had similar feedback to that of the trainees explaining that percent change is not a common way of thinking or reporting on a patient. Percent change is relative and may have the potential to be misleading.

"I think percent change does provide more information, but it's a matter of thinking differently." S12

" I really struggle with percent change because the phenomenon is not linear and there is an implicit sort of implication in the concept that your denominator is either constant or is really relevant because it is a fraction." S11

Several staff physicians also noted that information in the trajectory visualization can be gleaned from the other graphs and showing the trajectory visualization is not necessary and redundant.

“Any trend I am looking for you would see in the timeline (other visualizations).” S10

Visualization Application

In the visualization application category alert, changes above a threshold, presence of absence of evidence, promoting looking beyond a threshold, and integration with other visualizations all emerged as subthemes. The integration with other visualizations was a subtheme that appeared across multiple visualizations and will be discussed in Section 5.2.5. The only subtheme that was identified in interviews with trainees was the alert subtheme.

The staff physicians described that the trajectory visualization would be very useful for a certain subset of patients, especially those in the acute stage. Several staff physicians noted that it may be valuable to include a warning or flashing with this visualization when the ICP is increasing significantly. However, other physicians explained that if the visualization is used as an alert, it may generate a lot of unnecessary phone calls and one physician highlighted that the ICU already has a lot of alarms going off and wasn't sure it was a good idea to add to this strain.

> *"(the goal is to) increase our ability to identify trends and synthesize information and decrease our cognitive load and everything is flashing, it's a bit of a problem." S3*

A few staff physicians explained that what they care most about are changes in ICP above a threshold and the percent change visualization will likely be ignored until the ICP approaches a threshold where you are worried.

> *"A lot of neuro is threshold driven, not that we always know what if the threshold for that specific patient…So, I think a lot of this will end up being dismissed at the end until you maybe get close to the borderline values where you're worried." S7*

Several staff physicians also explained that it is important to have an evidence-based approach and unless there is a decision that can be made from quantifying the percent change, this is not a valuable edition.

> *"I am not sure the benefit of quantifying it unless the quantification is associated with specific thresholds…If percent change is associated with a sign of treatment response or that the treatment is failing, then in that case, it is important to quantify." S17*

> *"So, I think because there's not a lot of empirical evidence about what those numbers mean, all I'm really caring about is when it's crossing the threshold and how many times it has crossed the threshold, how much time you spend above that threshold which you've already done with the others (visualizations)." S10*

On the other hand, there were staff physicians that emphasized that regardless of the evidence, they cared about all changes in ICP, and it is hard to know the value the visualization may bring until it is integrated into the physician's workflows. They explained that physicians may not know what they need in a display and there may be enormous value in including certain elements, even though people don't claim to see value in them.

"I can understand why a trainee may not care (referencing percent change), but for me. I care. I may not know what to do with it, but I am going to put pressure on science to tell me what to do with it." S8

"As people become accustomed to looking at this information, they may start to make sense of it and use the information to help inform decisions." S2

"The fact is you do need it (trajectory visualization), you just don't realize you need it so some of this is sneaking in user-friendly, intuitive interfaces that are some types of analytics into people's conscience of what they get used to seeing, and then they realize it's valuable." S2

The staff physicians noted that novices tend to think in absolutes and thresholds, but this is not how patients are treated. One staff physician explained an example of a trainee who was convinced that one patient was in much worse condition at an ICP of 22mmHg than another patient at 18mmHg. However, this is not always the case, and it is important to look beyond thresholds and focus on the trajectory. In general, the staff physicians were uncertain about how exactly the visualizations would be used but they acknowledged that the visualization promotes looking beyond a threshold.

5.2.4 Summation Trend Chart

The summation trend chart visualization themes and subthemes are presented in the following sections.

5.2.4.1 Themes

Table 28: Staff physician themes for summation trend chart. Starred subthemes appear as trainee subthemes.

Theme	Subtheme	Description, Quote, or Example
Content Feedback	Importance of CPP Targets*	Comments that mentioned the importance of CPP targets in neuro-critical care. The physician commented that they focus a lot on optimal CPP and adjusting this goal and this could be added to the visualization. S16
Usability	Challenges identifying individual variables*	Comments that revealed challenges or expressed concern about the usability of the summation graph, specifically for detecting the individual variables. The physician described that in emergencies, you want to be able to see what is going on and it is hard to appreciate the changes in the individual variables in the summation graph. S3
Visualization application	Autoregulation	Any comments made by the staff physicians that described how the patient's autoregulation can be interpreted by the visualization. The physician noted that they can tell if a patient is autoregulating with the visualization. S8
	Relationship of variables*	Any comment that mentioned that the visualization has application for visualizing the variables and the relationship of MAP, ICP, and CPP together. The physician commented that they like to look at the variables (ICP, CPP, and MAP) together and think of MAP and ICP as independent variables, and CPP as the derived variable. S11
Design Preferences	Line graph	Any comments that indicate a preference for the line graph version of the visualization.
	Advanced summation trend chart	Any comments that indicate the value of the advanced summation trend chart.
	Summation graph	Any comments that indicate a preference for the summation trend chart.

Content Feedback

The importance of CPP targets emerged as a subtheme with the staff physicians as well. The staff physicians emphasized the importance of CPP and noted that it is important that a visualization with CPP is included on the display. The staff physicians explained that because the other visualizations captured ICP, it would be valuable to make the focus of the visualization CPP and ICP and MAP the background players. A couple of physicians noted that they would also like to see targets for CPP and a visualization like the individualized threshold visualization for CPP.

Visualization Application

The staff physicians commented that the summation trend chart has an application for showing the relationship between variables and the autoregulation of a patient.

One staff physician explained that they like to look at MAP, CPP, and ICP together and think of MAP and ICP as the independent variables and CPP as the derived variable. The physician further explained that there are many independent reasons why MAP and ICP would go up and CPP is the net result. They commented that the summation trend chart can help with visualizing when CPP is inadequate, and which independent variable (ICP or MAP) may be the culprit. The staff physicians agreed that the relationship between these variables is very important, however, there was inconsistent feedback on whether the summation graph was the right way to visualize this.

The goal of the summation trend chart is to show the relationship between the key hemodynamic variables and help give clues for the autoregulatory status of a patient. When a patient's autoregulation is intact, ICP should remain stable as the MAP adjusts to make up for changes and spikes in the CPP (Silverman & Peterson, 2022). Several staff physicians noted that they were able to detect if a patient is autoregulating and understand the optimum CPP by looking at the summation trend chart. However, one physician highlighted that they have a very solid grasp of these concepts and someone less experienced may not be able to infer autoregulation or optimum CPP from the visualization.

Usability

Consistent with the trainees, the staff physicians commented that it is challenging to identify the individual variables with the summation trend chart. The physicians explained that it is especially difficult to see if ICP is going up or down when the variables are stacked on top of one another. One suggestion was to colour the line for changes in ICP to eliminate this confusion.

Design Preferences

To address the usability challenges with the summation graph, several other visualizations were explored as the interviews were conducted. The staff physicians noted that showing the relationship of the variables in one visualization is valuable, however, there were concerns about not being able to appreciate the changes in ICP. Below, Figure 22 shows two additional iterations of the visualization to help address this concern. The data represented in each of these visualizations is the same.

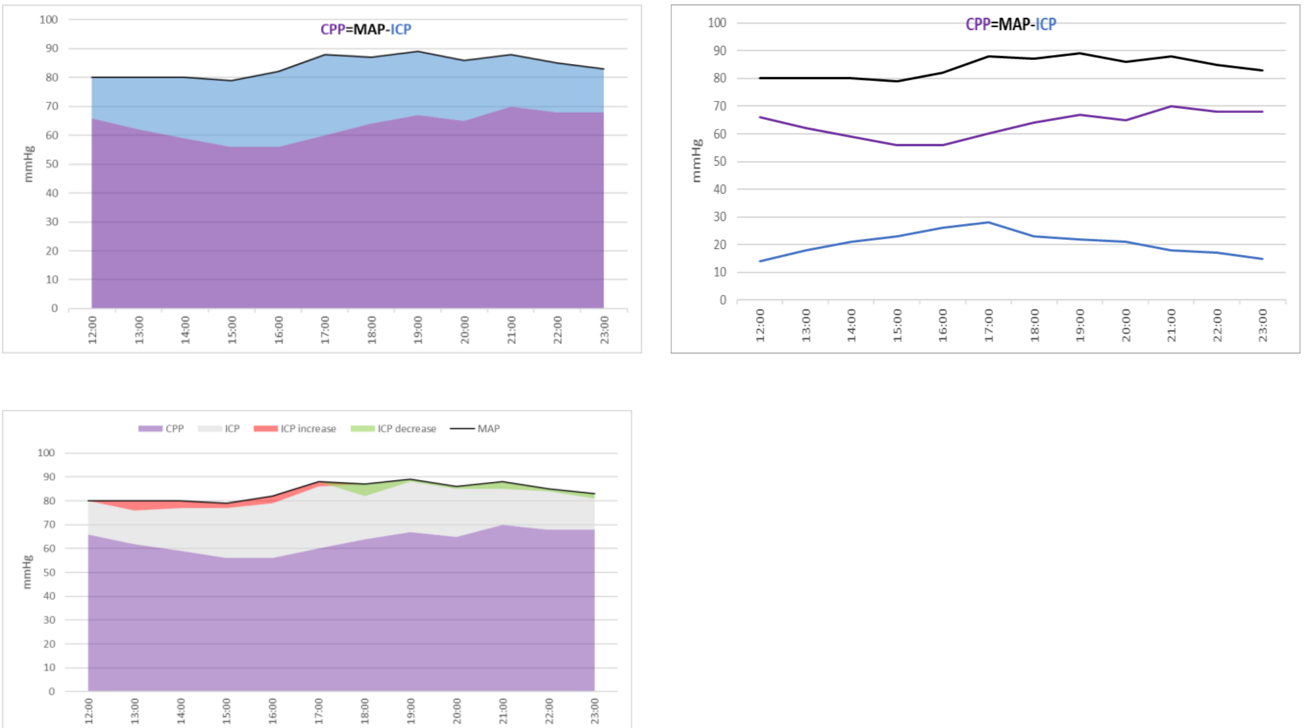


Figure 22: Various design iterations of the summation trend chart to show the relationship between MAP, CPP, and ICP.

The top left representation is the original summation trend chart with CPP on the bottom, ICP on top, and the sum representing MAP. The top right representation shows the variables as three separate lines without stacking them on top of each other (line graph). The bottom left representation shows CPP on the bottom, ICP stacked on top, and highlights the amount that ICP has increased or decreased with a red or green area (advanced summation trend chart). The staff physicians had varied feedback regarding the different visualizations. Some staff physicians thought that the advanced summation graph was quite complicated, and the line graph is the easiest visualization to understand. They also explained that the line graph is the easiest to appreciate the changes in the individual variables which addresses the concern with the summation graph. One staff physician noted that the line graph is more familiar and therefore may be configured more easily at the bedside, especially for novice users. A couple of physicians appreciated the original version of the summation trend chart as it was easier to understand than the advanced summation graph, yet still showed the relationship between the variables.

Several staff physicians noted that the advanced summation trend chart offers a lot of information about the autoregulatory status and explained that although it may take more effort to process and require a greater understanding of the concepts, it has application for more advanced learners.

"I think it would be a little harder to grasp and to teach because it is not the way that we've done things in the past, but it doesn't mean it isn't what we need to think of for the future….I think the straight lines are easier and more basic, but I really like the next one (summation with red/green area) for some kind of more in-depth knowledge" S12

*"When you start doing things like that and forcing you to look at your instrument (referring to more complex visualizations), you can get more out of it." S11*One staff physician thought that the line graph and the summation trend chart were less informative than the advanced summation trend chart and the advanced summation trend chart helped physicians think about autoregulation.

"I think the top two are less informative, so I don't want people to get used to looking at them, in part because they wouldn't be able to make any inferences about things…The bottom one has a lot more information even if it is more complex." S18

5.2.5 General

The themes and subthemes that appeared across multiple visualizations and were agnostic of any visualization are presented in the following sections.

5.2.5.1 Themes

Table 29: Themes and subthemes that appeared in multiple visualizations or independent of a specific individualization (Staff)

Theme	Subtheme	Description, Quote, or Example
Content Feedback	CPP dose*	Comments that indicated a desire to visualize CPP as a dose. The physician commented that they would like to see the bar chart (ICP dose) for CPP above/below a target. S14
	Other parameters	Any comments that highlighted additional variables that are important in neuro-critical care. The physician commented that end-tidal CO2 is another important variable in neuro-critical care. S10
	ICP Waveform*	Comments that described the importance of ICP waveform in neuro-critical care and understanding the patient's condition. *"The changes in the character of the waveform are often really important to me." S8*
Physician Training	Learning curve	Any comments that described the learning curve with new interfaces and differences between experts and novices. *"When you do it five times, then you're actually better than you were before even though the first five times felt a bit awkward." S11*
Visualization/ General Usability	Accessibility	Any comments that discussed the accessibility of the interface for different users. The physician commented that it will be important that all the visualizations are readable for someone who is colour blind. S9
Visualization Interaction	Time Scaling*	Comments that discussed different time periods that would be important or desire to zoom in and out of the visualization. The physician commented that the timeline of change is important as some changes occur quickly, some over longer periods. S5
	Target Customization*	Comments that discussed the value of individualizing ICP targets. *"For example, for certain patients we talked to the neurosurgeons, and they tell us we don't want the ICP above 12 in this patient. For example, in any other patient, we wouldn't even bat an eyelash over, but for this particular patient there might be some pathology that's particular that we need to consider." S1*

Table 30 (cont'd): Themes and subthemes that appeared in multiple visualizations or independent of a specific individualization (Staff)

Theme	Subtheme	Description, Quote, or Example
Visualization Interaction (cont'd)	Exact Values*	Comments that mentioned that knowing the exact value of variables is beneficial either through showing them directly on the visualization or through interface interactions. The physician appreciated the occasional ICP readings for the peaks and valleys of ICP on the individualized threshold visualization. S8
Visualization Application	Monitoring type*	Any comments that highlighted the visualization application for different types of ICP monitors. The physician explained that all ICP monitoring is not continuous and used an EVD as an example. S12
	Different users*	Comments that highlighted that there are various users of the bedside physiologic monitor and preferences and needs may vary. *"Different levels of providers may benefit from different types of presented information." S2*
	Integration with other visualizations*	Any comment that mentioned that this visualization would be valuable alongside other visualizations. The physician mentioned that the individualized threshold visualization is valuable and addresses some concerns they had by only showing the dose visualization. S11

Content Feedback

The content feedback theme involved any comments made by the staff physicians about other content to consider on a bedside physiologic monitor. The three subthemes in this category include other parameters, ICP waveform, and CPP dose.

The experts explained that it is important to look at not only ICP but ICP in the context of other variables and there are other parameters and pieces of information that are important in neurophysiology. The other parameters that were brought up by staff physicians include:

- PRx
- Ventilation
- End-tidal CO2
- Brain Tissue Oxygenation
- Blood Pressure
- Heart Rate
- Clinical Exam
- Pupil Diameter

Another subtheme that emerged was waveform analysis and the importance that this has on patient management. This also came up in the interviews with trainees. The experts explained that in addition to an ICP threshold of concern and trajectory of a patient, examining the ICP waveform can reveal a lot of information about what is going on with a patient. ICP waveform analysis can help provide information about a patient's brain compliance and whether they are at risk for increases in ICP and decreases in CPP which can contribute to secondary brain injury (Kirkness et al., 2000).

> *"A number per se, sure it's important. Don't get me wrong. But the more I do my job, the more I realize the number per se… I can kill a patient with a good number. Because there is other information that I am often not aware of." S8*

The staff physicians emphasized that looking at the value of ICP alone will result in missing important information about a patient's outlook and waveform analysis can help with understanding the status of the brain.

> *"The changes in the character of the waveform are often really important to me." S8*

Physician Training

The staff physicians emphasized that there will be a learning curve with any new interface, especially for trainees. Several physicians noted that they often aren't fully aware of the value a tool will provide until it is incorporated into their workflow and thought process. One physician explained that even though there may be an initial objection to new visualizations, they may still provide value on a display and further usability testing will help understand this.

> "*I think what you'll both find is that when you go to people like me, you may get an initial objection…. When you do it five times, then you're actually better than you were before even though the first five times felt a bit awkward." S11*

There was discussion about the differences between trainees and staff physicians and what they may think they want in a display. Experts tend to want more information and they know how to make sense of it, while trainees may be overwhelmed by complex visualizations.

"Experts what tons of information because they know how to deal with it. That is the thing that trainees hate… (trainee says) why are you putting so many data at me that I don't even know how to process?" S16

Usability

Accessibility of the visualizations emerged as a subtheme in the usability category across multiple visualizations. Several staff physicians noted it will be important to test the visualizations to ensure they are distinguishable for individuals with colour deficiency. This is discussed further in Chapter 6-Final Design.

Visualization Interaction

In the visualization interaction category, the subthemes time scaling, target customization, and exact values appeared in multiple visualizations and these subthemes were consistent with the interviews with the trainees.

The staff physicians mentioned that the ability to customize the time frame for the visualization would provide value and the time frames presented in the visualizations are appropriate default views. The hourly grouping of the ICP dose bar graph was appreciated and the staff physicians explained that the aggregation of data in 1-hour periods makes it easier to interpret and see trends in the data. Several time frames were discussed for the trajectory visualization including 24-hour, 6-hour, and 1-hour periods. The physicians explained that depending on the patient and disease stage, customization would be critical.

The staff physicians agreed that there is value in having the ability to customize ICP target ranges for each patient on the visualizations, however, they also believed it was important to have a default view. One physician further noted customization would only be done by a few experts on the team and that even experts may not know how to individualize the ranges from patient to patient.

"I think some adaptability would be important for this tool to stay meaningful otherwise it will lose a bit of its utility." S7

“There's value in having a consistent way to report findings across patients. So, I worry that if everyone gets a different red, yellow, green threshold then you will have to recalibrate yourself at every bedside." S13

One physician explained that it is common for neurosurgery to give a target value for ICP, and this is currently challenging to track. They noted that an interface that allows this to be tracked and visualized would be helpful.

"For example, for certain patients, we talked to the neurosurgeons, and they tell us we don't want the ICP above 12 in this patient. For example, in any other patient, we wouldn't even bat an eyelash over, but for this particular patient there might be some pathology that's particular that we need to consider." S1

The staff physicians also noted that knowing the exact values of variables, whether that be from interface interactions or through occasional number readings on the interface would be valuable on the interface.

Visualization Application

In the visualization application category, different users, integration with other visualizations, and monitoring types were three subthemes that emerged across multiple visualizations. Integration with other visualizations and monitoring types also were subthemes from the interviews with trainees.

The staff physicians noted that there are multiple users of the bedside physiologic monitor, and different users will have different goals with the monitor.

"Doctors are primarily interested in diagnosis and nurses are primarily interested in care. So, a nurse might like one sort of way of looking at data because they are interested in minute-to-minute care, whereas doctors are going to be interested in pattern recognition for diagnosis." S11

One physician noted that the individualized threshold visualization or trajectory visualization may be useful for a nurse to notify the physician if an acute change is happening at the bedside. The physician’s acknowledged that the person most likely to notice something on the bedside physiologic monitor may not be the most experienced, and it is crucial to display information in different ways to accommodate different users.

“Different levels of providers may benefit from different types of presented information” S2

The staff physicians noted that the visualizations will be most valuable when they are integrated and that many of the visualizations are complementary to one another. The staff physicians explained that the information on the individualized threshold visualization was useful and complimentary to that of the ICP dose visualizations. One physician explained that individualized threshold visualization that shows continuous ICP values and trending is something that needs to be part of any interface.

“(Individualized Threshold Visualization) is basic and intrinsic and needs to be part of any system.” S2

The trajectory visualization was regarded as a useful addition to some of the more detailed visualizations, and a couple of staff physicians noted that it could potentially be integrated into the other visualizations.

The monitoring type for the visualizations was another theme that emerged in the interviews. The staff physicians explained that the visualizations may appear different from real ICP data, and the representations showed look clean with little noise. The physicians acknowledged that the visualizations are most effective for patients with continuous ICP monitoring through a parenchymal monitor rather than an external ventricular drain (EVD) that is also being used to drain cerebral spinal fluid (CSF). For patients that are using an EVD to measure ICP that is also being used as a drain, the ICP signal can only be transduced when the drain is clamped, and therefore, continuous ICP readings are not possible (Nag et al., 2019). As an example, the ICP dose visualization would not be possible for those patients that only have intermittent readings of ICP as the visualization relies on continuous monitoring to visualize the time spent in ICP ranges.

5.2.6 Overall Prioritization

At the end of each interview, the staff physicians were asked to choose which visualizations they would appreciate most on a bedside physiologic monitor. They were told that they could choose none or as many as they believed would provide value. Like the prioritization scores for trainees, the prioritization was given a percentage score based on how many participants selected the visualization out of the total number that was asked for prioritization of the visualization. The prioritization scores can be seen below in Table 31.

Table 31: Overall prioritization scores for all visualizations (staff)

	# Participants Evaluated	*# Participants Prioritized*	*Prioritization Score*
ICP Dose-Bar Chart	11	10	**91%**
ICP Dose-Donut Chart	11	5	**45%**
Individualized Thresholds	11	6	**55%**
Trajectory	11	3	**27%**
*Summation Trend Chart**	11	8	**73%**

** Prioritization scores include any version of this visualization. Some participants noted they would appreciate this visualization as a line graph rather than a summation trend chart*

The staff appreciated the ICP dose bar chart the most followed by the summation trend chart and individualized thresholds. Many staff physicians commented that the trajectory and ICP dose-donut chart (summary) visualization would be most valuable if integrated with the other visualizations. Compared to the trainees, more staff physicians prioritized the ICP dose-bar chart (91% vs. 53%).

5.3 Discussion

The goal of the interviews with staff physicians was to discuss and validate the designs, as well as iterate the designs to address concerns. The interviews were also used as an opportunity to discuss improvements to the designs and capture ideas for additional content on a bedside physiologic monitor. The results of the interviews with staff physicians combined with the feedback from the preliminary usability assessment with trainees were used to guide the design of a final interface prototype that will be tested in a usability study currently being conducted (January-March 2023). All the comments from trainees and staff were analyzed and there were several design impacts on the final design. The results of the interviews were discussed with our SME, Dr. Victoria McCredie, and further validated for any conflicting comments. Several themes were not addressed, and we have provided recommendations for future work. The next two sections describe the impacts on the design and recommendations for future work.

5.3.1 Impact on Design

The staff and trainee feedback and their associated design impacts are displayed in Table 32 and discussed in the following paragraphs. Many of the themes that arose in the interviews with trainees and staff were positive and emphasized the importance of collating information onto a single display. The general comments for multiple visualizations led to interface interactions including time scaling, target customization of ICP ranges, and hover-over interactions to show the exact values of variables. The staff physicians highlighted that different users will use the information differently, therefore the final interface needed to include varied complexity of visualizations. Additionally, allowing users the option to toggle variables on or off to visualize the information differently increases usability consistent with 1 of Nielson's usability heuristics-flexibility and efficiency of use (Norman & Nielson, 2013). The accessibility of the visualizations for individuals with colour deficiency was brought up by the staff physicians and this was something that was addressed in the final design outlined in Chapter 6.

ICP Dose

The ICP dose visualizations (bar chart and donut) had several visualization usability themes from the usability assessment with trainees and these themes are addressed with interface training. In the interviews with trainees, once the visualization was explained, the trainees did not have additional questions which suggests that appropriate training on the visualizations will eliminate any user confusion. The wording of the left y-axis and percent time at ICP intensity was discussed with the staff physicians. The staff physicians noted that ICP Time Burden would be a more appropriate title, despite acknowledgment that 'burden' may not be immediately understood by all trainees. An explanation of what burden means and how it applies to the visualization is therefore a requirement in interface training. There was some confusion regarding the two axes on the bar graph and the stacking order of ICP intensities. In stacked graphs, it is easiest to appreciate the changes in the bottom variable. For the ICP dose visualization, it was most important that the changes in the high ICP range were understood, therefore we kept the high ICP proportion at the bottom of the graph. We have provided users with the option to turn on/off the secondary y-axis (average ICP) and the ICP burden proportions to visualize one variable at a time. Both staff and trainees identified that the fluctuations and peak value in ICP are very important therefore, the max value was included in the hover interface interaction on the bar chart. Staff physicians also highlighted the importance of the duration of ICP events. This is addressed by anchoring the interface on the ICP dose bar chart and allowing users to click on the hour of interest and view the individualized threshold and summation trend chart visualization. This will allow users to see what the proportions in the ICP dose bar chart are comprised of and the durations of those ICP events. A concern that was raised by staff physicians was differentiating a patient who has a moderately high ICP from a patient with a very high ICP explaining that the visualization would not discriminate between these two patients. A fourth ICP intensity, very high, was added for ICP values greater than 30mmHg.

Individualized Threshold

The individualized threshold visualization had higher understanding scores than the dose visualizations amongst the trainees. One trainee noted that they were confused about the colours represented on the individualized threshold visualization, however, once explained there was no further confusion. The staff physicians explained that the individualized threshold visualization is critical to understand the nuances that a summary visualization such as ICP dose or trajectory lacks. Both staff and trainees explained that the individualized threshold visualization would benefit from the addition of annotations such as medication, patient position, and neurosurgical procedures to understand how the patient is responding to these events. Therefore, annotations were included in the final design discussed in Chapter 6: Final Design. The design of the individualized threshold visualization had varied comments from trainees and staff physicians. Overall, it was acknowledged that is important to consider what is being displayed together on the interface. According to the Gestalt principle of similarity, humans build a relationship between similar elements in a design, and this can be achieved by using colour or shape (Koffka, 1935). The ICP dose visualizations show ICP dose proportions stacked on top of one another to represent the amount of time spent in that ICP intensity range. The individualized threshold visualization shows the ICP trend over time and also shows the ICP intensity ranges. Although there are similarities between these two visualizations, the

ICP dose visualization does not display the targets on the visualization. It was important to consider these visualizations together and ensure that there was consistency, yet a distinction between the visualizations. Below, Figure 23 presents one version of the individualized threshold visualization next to the ICP dose visualization.

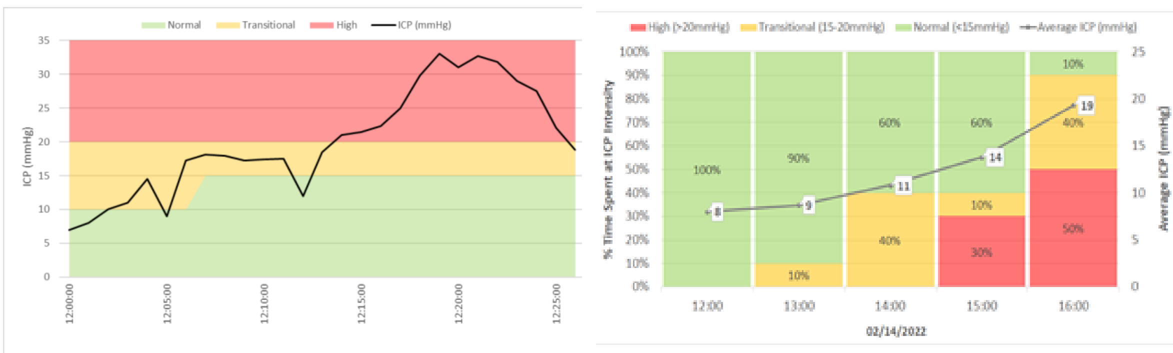


Figure 23: Individualized threshold visualization 2 next to the ICP dose bar graph

Figure 23 demonstrates that showing the left version of the individualized threshold visualization on the same interface as the dose visualization may confuse users. On the left visualization, red is at the top of the visualization because the y-axis displays ICP from low to high. On the dose visualization (right), the y-axis represents the proportion of time spent at various ICP intensities to sum to 100%. The high ICP proportion is included on the bottom of the stack as it is easier to appreciate the changes in the bottom variable in stacked charts. There is a significant visual similarity between these visualizations despite showing different concepts. In the interviews with physicians, the individualized threshold visualization with the dashed line for targets was noted as familiar and less likely to be confused with the ICP dose visualization (see Figure 24 below).

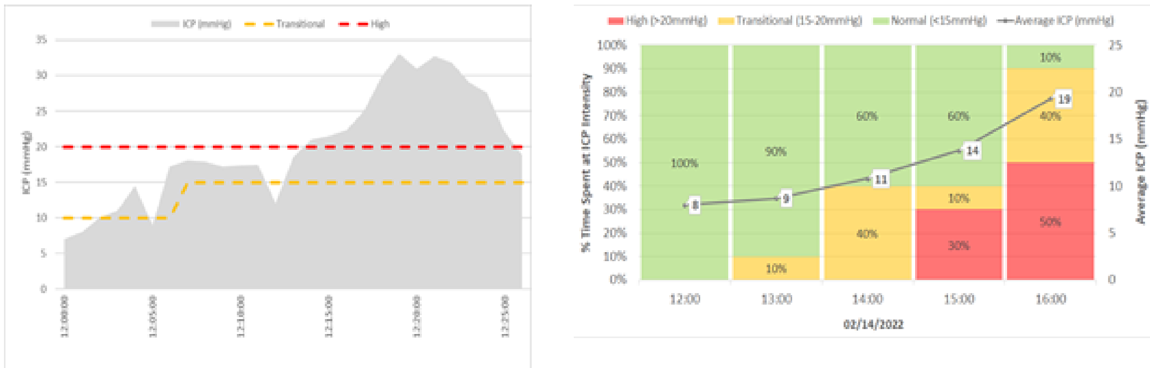


Figure 24: Individualized threshold visualization 1 next to the ICP dose bar graph

For these reasons, the individualized threshold visualization with the dashed lines for thresholds was selected for the final design prototype which is discussed further in Chapter 6: Final Design. In future work, we recommend an investigation of the effectiveness of various visualizations.

Trajectory

The trajectory visualization was generally regarded as valuable as an addition to a display, but not on its own. Staff physicians described this visualization as a useful way to alert a physician to pay attention to a patient who may have a rapidly rising ICP (high percent change) despite being below a threshold of concern. There was some confusion on the interpretation of the percent change and what the trendline indicated in the usability assessment with trainees, therefore, this is included in the interface training. The visualization was regarded as an alert and summary visualization which resulted in placement on the first screen of the interface. A few staff physicians noted that they care most about changes above a threshold and others noted they care about all changes. The minimum, maximum, and average ICP will be displayed adjacent to the trajectory visualization so physicians can correlate the change to actual values in ICP. Preferences for the gauge and trendline trajectory visualization were varied, however, including the trendline provided more context for when in the time frame the ICP was low or high. The importance of the trend of ICP was highlighted by trainees and staff, therefore, the trendline style of visualization was selected.

Summation Trend Chart

The main feedback received for the summation trend chart was the challenges associated with identifying the changes in individual variables in stacked charts, especially the middle variable (or the variable that represents the top area of the stack). Despite these challenges, the trainees and staff physicians noted that visualizing representing the key hemodynamic equation (CPP=MAP-ICP), was valuable to show the relationship between variables. Several staff physicians also noted that with visualization, they can identify when the patient is autoregulating. Staff physicians were shown a more complex version of the summation trend chart (advanced summation trend chart) with increase and decrease areas to highlight changes in ICP. There was inconsistent feedback on the value of a more advanced visualization and discussions with our SME led to the continuation of the simple summation trend chart. In future work, we recommend an investigation of the effectiveness of various visualizations on perception and performance. To address the challenges of identifying the individual variables, there are several design impacts:

- Display the visualization above the individualized thresholds visualization which only shows ICP (hardest variable to detect in the summation trend chart)
- Hover over interaction for the exact value of the variables
- Allow users to toggle variables on/off to view one variable at a time

The themes, subthemes, and their associated design impacts on the visualizations and general comments are summarized in the table below.

Table 32: Staff and Trainee feedback and design impacts. Themes that are followed by an *, emerged in both interviews.

Visualization	Theme-Subtheme from interviews	Design Impact
General	- Usability-Accessibility	Test visualizations against various colour deficiencies.
General	- Visualization Application-Different Users	Include a combination of simple and more complex visualizations and allow users customization options (i.e., time scaling, toggling of variables).
General	- Visualization Interaction-Time Scaling*	Allow users to zoom in and out of the timeline and allow users various time scaling options for the trajectory, and ICP dose summary.
General	- Visualization Interaction- Target Customization*	Allow customization of ICP targets but have default values for ranges.
General	- Visualization Interaction-Exact Values*	Hover over interaction to show the exact values of variables on the visualizations.
ICP Dose	- Visualization Usability-Interpretation of ICP burdens and percentages - Visualization Usability-Wording of y-axis* - Usability-Intuitiveness*	Explain visualization in the interface training video.
ICP Dose	- Visualization Usability- Wording of y-axis *	Label the left y-axis ICP Time Burden.
ICP Dose	- Visualization Usability-Two axes in context with graph*	Optionality to turn variables off and visualize one y-axis at a time (customization).
ICP Dose	- Visualization Application-Trend*	Include the trendline next to the ICP dose summary visualization as the dose summary (donut) does not show the trend.
ICP Dose	- Distribution of ICP values-Average*	Keep the average line to show the trend and optionality to turn on/off.
ICP Dose	- Distribution of ICP values-Fluctuations in ICP*	Hover over interaction to show the max value of ICP.
ICP Dose	- Usability-Differentiation of higher ICP values	Include a fourth ICP intensity category for very high ICP (greater than 30mmHg).
ICP Dose	- Distribution of ICP-Duration of ICP events	Anchoring the visualization on the dose visualization and allowing users to click on the hour to see the more detailed visualizations and what the burdens are comprised of.
Individualized Thresholds	- Visualization Usability-Interpretations of the colours of ICP intensity ranges	Explain visualization in the interface training video.
Individualized Thresholds	- Visualization Usability-Detection of threshold change	Include ICP target ranges alongside the visualization.
Individualized Thresholds	- Content Feedback-Annotations*	Include annotations on the interface.
Individualized Thresholds	- Design Preferences-All Subthemes	Consider what is being displayed together on the interface and display visualization that is consistent, however, distinct from the dose visualization to avoid confusion.

Table 33 (cont'd): Staff and Trainee feedback and design impacts. Themes that are followed by an *, emerged in both interviews.

Visualization	Theme-Subtheme from interviews	Design Impact
Trajectory	- Visualization Usability - Interpretation of Percent Change - Visualization Usability-Trendline Visualization	Explain visualization in the interface training video.
Trajectory	- Visualization Application-Alert - Visualization Application-Presence or Absence of Evidence - Visualization Application-Promotes looking beyond a threshold	Display visualization on the first screen of the interface.
Trajectory	- Visualization Application-Changes above Threshold - Visualization Interaction-Exact Values	Display visualization alongside the min/max ICP value.
Summation Trend Chart	- Visualization Usability-Challenges identifying individual variables* - User confusion-Legend	Explain visualization in the interface training video.
Summation Trend Chart	- Visualization Usability-Legend	Include a standard legend in addition to the equation above the visualization.
Summation Trend Chart	- Visualization Usability-Challenges identifying individual variables*	Display alongside individualized threshold visualization (only shows ICP) and keep ICP on the top of the summation graph (hardest variable to detect).
Summation Trend Chart	- Visualization Usability-Challenges identifying individual variables*	Allow users to toggle variables on/off to view one variable at a time.
Summation Trend Chart	- Visualization Usability-Challenges identifying individual variables* - Visualization Interaction-Exact Values*	Hover over interaction for exact values of variables.
Summation Trend Chart	- Visualization Application/Physician Training-Autoregulation	Include cues on the interface to check for autoregulation.
Summation Trend Chart	- Visualization Application-Relationship of Variables - Design Preferences-All Subthemes	Display the simple summation graph version of the visualization as it shows the relationship of the variables and address usability concerns around identifying the individual variables.

5.3.2 Future Considerations

Several themes and subthemes arose in the interviews with both groups that were not addressed in the final design presented in Chapter 6. Several considerations for future work are outlined below:

- **Feedback from different users:** Staff physicians highlighted that many users interact with the bedside monitor including nurses. We recommend that other groups be involved in usability testing and design iterations to ensure the visualizations are understood and meet the requirements of other groups that may benefit from the advanced display.

- **Effectiveness of different visualizations:** In this study, we focused on addressing usability concerns and any user confusion about the presented visualizations and we also collected preferences for a few visualizations. The effectiveness of different visualizations on understanding and perception was not included in this study however, this will play an important role in interface usability.

- **Implication of percent change in ICP:** This was a theme that was brought up with both trainees and staff, however, the staff explained that regardless of the implication, it is important information that they would like to see. For future work, we recommend a study to understand the impact that percent change in ICP may have on patient outcomes.

- **Importance of CPP Targets and CPP Dose:** Optimum CPP, the importance of CPP targets, and the interest in a CPP dose visualization (like the ICP dose visualization) were all comments that arose in the interviews with trainees and staff. The focus of the final interface prototype described in Chapter 6 is ICP. However, we recommend future work explore different visualization for CPP targets or apply similar visualizations for this variable.

- **Monitoring Type:** The visualizations presented were designed for continuous ICP monitoring although there are situations where ICP monitoring is done through an EVD and therefore is not continuous. In future work, exploration of the presented visualizations in non-continuous ICP monitoring is recommended.

- **ICP Waveform Visualizations:** ICP waveform analysis is an integral part of neurophysiology, and this was highlighted by a few comments in the interviews with trainees and emphasized by the staff physicians. In the early design process, we chose to not continue with waveform visualizations due to challenges previously discussed however, future work should focus on how we can extract the waveform peaks to display this in a usable format for both novices and experts.

- **Autoregulation visualizations:** The staff physicians noted that the summation trend chart allows them to identify whether the patient is autoregulating although this was not something that the trainees identified. We have incorporated a notification for autoregulation into the final design described in Chapter 6 to help cue trainees to investigate a patient's autoregulatory status. Other indices should be explored on an ecological display such as PRx which may make autoregulatory status more obvious for trainees.

- **Other neurophysiologic parameters:** The staff physicians noted several other neurophysiologic parameters that are valuable for patient diagnosis, treatment, and management in neuro-critical care. The parameters that were discussed include brain tissue oxygenation, Prx, ventilation, end-tidal CO2, blood pressure, heart rate, clinical exam, and pupil diameter. Although many of these parameters are included on the real-time bedside physiologic monitor and therefore will still be displayed in the standard monitor + EID visualizations, future work should explore the integration of these other parameters in the EID visualizations. Our visualizations focused on ICP as the main variable of interest.

5.4 Conclusions

The results of the design refinement and feedback elicitation with staff physicians dictated the impact on the final design. Several recommendations for future work arose from the discussions and are discussed further in Chapter 7. The next chapter outlines the final design combination and creation of the interface prototype that is currently being tested in a usability study with trainee critical care physicians (January-March 2023).

Chapter 6
Final Design

Based on the feedback provided by staff physicians and the outcomes of the preliminary usability assessment with trainees, the designs were updated and combined on an interface prototype. The interface prototype was later used in a usability assessment (January-March 2023) with trainees to evaluate performance, mental workload, situational awareness, user confidence, and usability of the standard interface with the EID visualizations to the standard interface. The standard interface was coded on a web dashboard by Rayyan Quraishi, a co-op student in the Advanced Interface Design Lab (AIDL).

6.1 Combining the Visualizations

As the interviews with trainees and staff physicians were conducted, the ongoing analysis took place, and a combined interface prototype was created based on feedback from the interviews. Some of the design impacts discussed in Section 5.3.1 determined the interface workflow and which visualizations would be displayed together. The design impacts that influenced the workflow of the interface are as follows:

- Display individualized threshold visualization on the same screen as summation trend chart visualization. These visualizations were regarded as the most detailed visualizations that would be looked at mainly to investigate if there was a problem. In addition, the individualized threshold visualization shows ICP by itself which addresses concerns with identifying the variable on the top of the summation trend chart.

- Display trajectory visualization and dose summary on the main screen (real-time monitoring) of the interface as they both serve as summary visualizations and the trajectory visualization can act as an alert.

When physicians described how they would look at data, they started with a high-level view and investigated more details if there were concerns. Therefore, it was determined that there would be three screens in the interface. The first screen would display real-time monitoring with the trajectory visualization and ICP dose summary. The second screen would include the ICP dose bar graph with 1-hour intervals, and the third screen would include the individualized thresholds and summation trend chart. An interface mockup in Figma was created and shown to 5 staff physicians at the end of the interviews. The comments received from the staff physicians are described below:

- The staff physician noted that they would only look at the individualized thresholds and summation trend chart if there was a spike in ICP that required investigation. *"Unless there was a spike in ICP, I would never look at data with such a fine lens."*

- The staff physicians explained that they would want to look at the ICP dose bar graph first and be able to dive into more detail (individualized thresholds and summation trend chart) if there was an issue.

- Percent change will be most useful on the first screen that the user sees.

- The physicians would like to be able to see the ICP dose summary first and then if there was a high burden, look at the ICP dose bar graph.

These comments support including the trajectory visualization and ICP dose summary on the first screen of the interface, allowing the user to look at the ICP dose bar chart and then dive into more detail with the individualized thresholds and summation trend chart.

6.2 Final Interface

The final interface prototype was designed with three screens. The three screens and what they included are described in the below sections. The final interface design took in feedback from the interviews with trainees and staff physicians as well as discussions with SME, Dr. Victoria McCredie who provided direction for certain details.

Vitals:	Real-time monitoring with the addition of ICP Summary (ICP burden summary, ICP trend, average/max/min ICP).
ICP Burden:	ICP dose over time (bar graph with 1-hour intervals) with annotations.
Pressures:	Individualized thresholds and summation trend chart with annotations.

6.2.1 Vitals

The first screen on the interface is the vitals screen (real-time monitoring) with the addition of an ICP summary on the right-hand side. The real-time monitoring section of the interface is modeled based on the Philips Intellivue monitor which is commonly used in hospitals in Canada. Below, Figure 25 shows the vitals screen of the standard interface with EID enhancements.

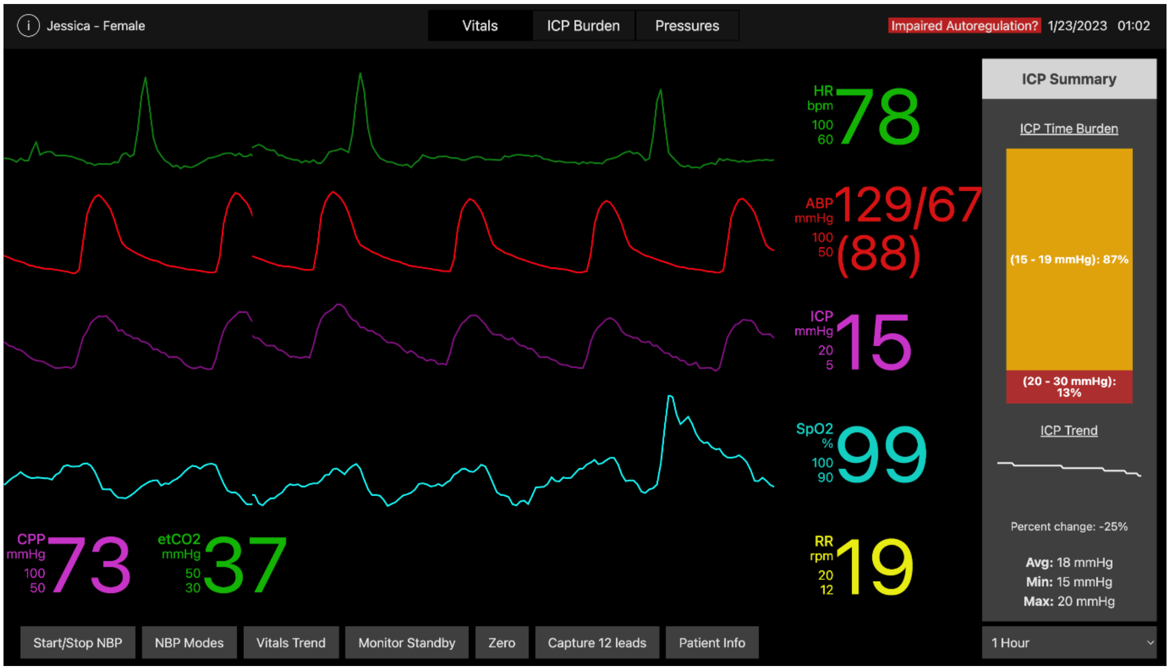


Figure 25: Vitals screen of final interface prototype. The real-time monitoring section of the screen was designed based on a Philips Intellivue monitor.

The ICP summary can be viewed for the past 1-hour, 6-hour, or 24-hour period as indicated by the time selector at the bottom of the summary. The ICP time burden bar shows the burden for the selected time period. In the interviews, the physicians explained they would like to see the ICP dose donut summary first and then be able to dive into more detail if the summary showed a high burden. The ICP time burden summary is shown as a bar rather than a donut visualization to optimize screen space as well as provide consistency with the ICP dose bar graph. The ICP trajectory and percent change, and the average/min/max are all provided below the ICP time burden summary. The trajectory visualization was regarded as something that may provide value as an alert and that is why it is shown on the real-time monitoring screen.

On the top header, an alert for potentially impaired autoregulation is included. In the interviews with trainees, it was acknowledged that autoregulation was not something they tend to think about. However, the staff physicians highlighted autoregulation as an important concept that needs to be considered. The trainees were aware of how to check for autoregulation even though it was not something they were normally doing unless asked by a staff physician. Therefore, an alert to check for potential impaired regulation will provide a cue for physicians to investigate a patient's autoregulatory status when they otherwise may not have considered this. The alert is activated when a patient's one-hour percent change is greater than 30% (and ICP value of more than 15mmHg, or if the patient's ICP is greater than 20mmHg (determined through discussions with Dr. Victoria McCredie).

The interactive elements on this screen include:

- Ability to navigate to other screens of the interface using the top header (Vitals, ICP Burden, and Pressures).
- Ability to select different time frames for the ICP dose summary using the drop-down arrow.

6.2.2 ICP Burden

The second screen on the interface is the ICP Burden screen (Figure 26). This screen shows the ICP dose bar chart for the patient, the set ranges for the patient's ICP ranges (normal, transitional, high, and very high), and annotations for events. Below the bar graph, the user can select the timeframe of interest using the slider or use the drop-down to select some standard time frames including 24 hours, 12 hours, or 6 hours. The annotations appear as a blue dot on the bottom of the bar graph and additionally on the time slider so the user is aware of when there may have been medication or treatment administered. When the user hovers over the bars, the percentages for each intensity range appear as well as the maximum ICP value for that time frame as the fluctuations and peak value of ICP was regarded as a critical element from the interviews with trainees and staff physicians.

The normal, transitional, high, and very high ICP proportions may be turned on/off by deselecting the box, and this functionality is also provided for the average ICP. In the proposed interface, there would be customization of the ICP intensity ranges, however, this screen is not available in the prototype as it was not a requirement for the usability study with trainees. The customization of ICP ranges was regarded as something that only the most senior staff in a unit would be involved in, therefore, this was not functionality that was required for the usability study. The user can click on the hour below the x-axis of the graph and by doing this, it will bring them to the pressures tab for that hour. This functionality allows the user to first start by looking at the ICP burden graph and then selecting an hour that they would like more detail of by clicking on that hour.

Figure 26: ICP burden screen of the final interface prototype.

The interactive elements on this screen include:

- Ability to navigate to other screens of the interface using the top header (Vitals, ICP Burden, and Pressures).
- Clicking on the hour of interest below the x-axis will navigate the user to the pressures tab for that hour.
- The interactive slider below the graph to navigate the timeline.
- Default time selections of 24 hours, 12 hours, or 6 hours by selecting the dropdown in the bottom right-hand corner.

- Filtering of annotations by type (i.e., patient position, medication, neurosurgical procedure, osmotherapy).
- Hover over interaction to show ICP burden percentages and max ICP value.
- Ability to turn on/off ICP burdens and average line by clicking the variable to visualize one variable at a time.

6.2.3 Pressures

The third screen on the interface is the Pressures screen (Figure 27). This screen displays the summation trend chart and the individualized threshold visualization on the same screen and there is a consistency of the colours between ICP in the summation graph and ICP in the individualized threshold visualization. In the summation graph, one of the challenges identified was appreciating the changes in ICP (top of the stack). Therefore, the summation graph has been shown above the individualized threshold visualization which shows ICP independent of the other variables. Consistent with the ICP burden screen, the annotations are viewed on the right-hand side and along the x-axis by a blue dot. Apart from the vitals screen which shows the variables in real-time, this screen provides a more detailed look at variables than the ICP burden screen. Staff physicians expressed that they would begin by examining the dose visualization and then if there was a high burden, they would like to see the details of the patient's ICP, CPP, and MAP during that time frame.

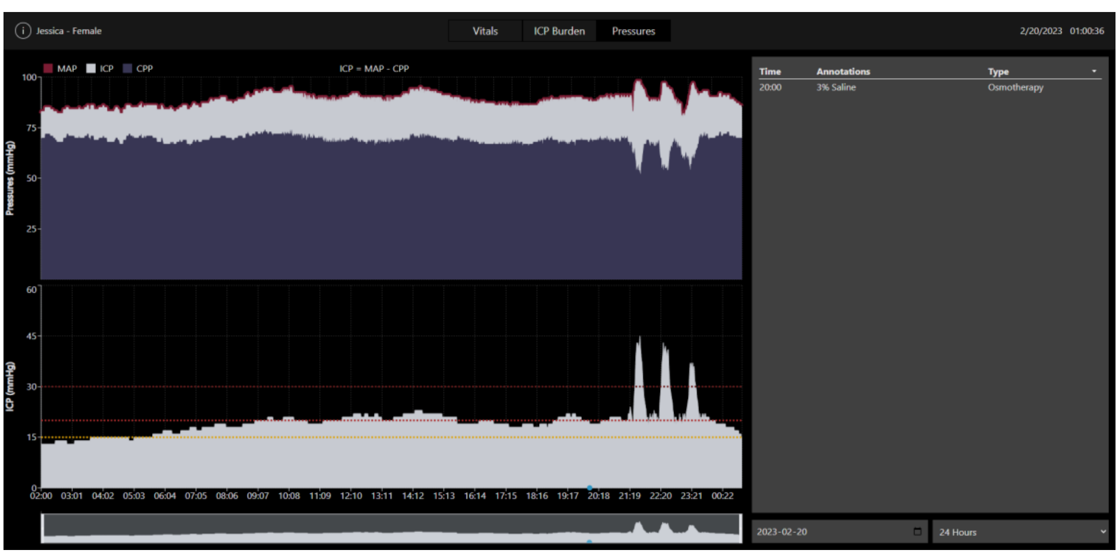


Figure 27: Pressures screen of final interface prototype.

The interactive elements on this screen include:

- Ability to navigate to other screens of the interface using the top header (Vitals, ICP Burden, and Pressures).
- The interactive slider below the graph to navigate the timeline.
- Default time selections of 24 hours, 12 hours, or 6 hours by selecting the dropdown in the bottom right-hand corner.
- Filtering of annotations by type (i.e., patient position, medication, neurosurgical procedure, osmotherapy).
- Hover over interaction to show the exact values of variables (ICP, MAP, and CPP).
- Ability to turn on/off variables in the summation graph by clicking on the legend box next to the variable.

6.3 Accessibility

When creating the final interface, the visualizations were tested using the colour-blindness simulator testing available online at colour-blindness.com (Coblinder, 2000). We uploaded the images for each visualization and evaluated different colour deficiencies to evaluate the accessibility of the designs. The three screens of the interface were tested against deuteranomaly, protanomaly, protanopia, and deuteranopia which are the four most common types of colour deficiency (National Eye Institute, 2019). The colours were distinguishable in the pressures screen for all colour deficiencies however, the ICP burden screen had some accessibility concerns for individuals with protanopia and deuteranopia which are two forms of colour deficiency that make it unable for individuals to see the difference between red and green.

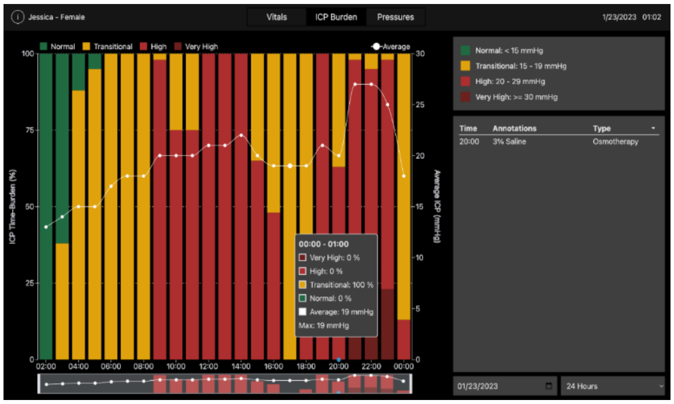
Figure 28 on the following page shows the ICP burden screen for these two types of red-green colour blindness. The same challenges persisted on the ICP summary panel on the vitals screen. As seen in Figure 28 on the following page, the differentiation between normal and high ICP burden is not distinct, especially for individuals with protanopia. Colours can be an effective way to communicate changes and alert nurses and physicians of potential hazards, however, designs in the critical care unit must be accessible and easily understood by all individuals providing care. Therefore, we recommend exploring ways to make the designs more accessible to all users in future work. Some ideas include using patterns in addition to colours on the display or experimenting with different colour combinations that are more distinct.

6.4 Interface Training

As previously noted, interface training will be a critical component in the use of the advanced display. In the preliminary usability assessment with trainees, users did not always have a full understanding of the visualizations, however, they were able to grasp the visualizations when they were explained. For the usability study with trainees (conducted Winter 2023-not discussed in this thesis), an interface training video was created for the participants. The interface training video script can be found in Appendix C.

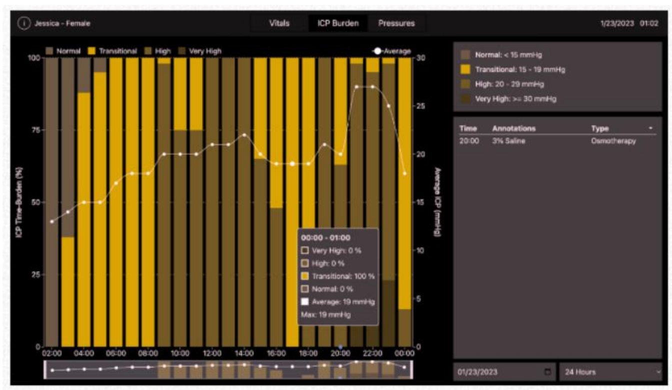
6.5 Conclusions

The combined interface was designed with feedback from both trainee and staff physicians and visualization usability elements from the preliminary usability assessment with trainees were addressed. The EID visualizations were integrated into a prototype that combines the Philips Intellivue bedside physiologic monitor with the new designs. This interface is currently being tested in a usability study with trainees in critical care to determine if the standard interface + EID visualizations have an impact on performance, situational awareness, confidence, mental workload, and usability. Testing for common colour deficiencies was performed on the final interface and the current version of the prototype proved challenging for individuals with protanopia and deuteranopia (red-green colour blindness). The interface also was not evaluated against medical device standards such as ISO-60601- Product Safety Standards for Medical Devices. In future work, this should be explored. The limitations of our work are discussed further in the final chapter of this thesis.



Typical vision

Protanopia



Deuteranopia

Figure 28: Evaluating the ICP burden screen against red-green colour blindness

Chapter 7
Conclusions and Future Considerations

In this chapter, the contributions and implications of this work are presented followed by the strengths and limitations of our work. We also provide recommendations for future work based on our findings.

7.1 Contributions and Implications

This work primarily supports the improvement of the quality of patient care and safety in critical care units. In addition, this work provides contributions to interface design in any complex socio-technical system in which users must make decisions with a lot of information and the impact of their decisions can be enormous. We aim to provide visualizations that can reduce the incidence of secondary brain injuries and enable clinicians to make better decisions thereby improving patient outcomes. Expertise development in a complex domain such as neuro-critical care takes years. If an interface can help accelerate this expertise development and teach complex concepts and relationships, experts may dedicate their time and resources to teaching other things. In addition, visualizations that integrate information allow for cognitive resources of physicians to be used elsewhere which will positively impact patient outcomes.

Beyond the ICU, this work including the visualizations also can be applied in other domains. The concept of a dose is not unique to ICP. The concept of dose exists in nuclear safety for radiation exposure (Joseph & Kim, 2021). The area under the curve for pharmaceuticals is another dose application (Scheff et al, 2011). This has also been applied to diabetes research for glucose monitoring (Ugi et al., 2016). This suggests there is generalizability of the ICP dose visualization for other applications.

7.2 Strengths and Limitations

This next section outlines the strengths and limitations of the study design and visualization (including the design process).

7.2.1 Study Design

The following are some strengths of the study conducted with both trainees and staff physicians:

- **Collection of rich data through 30 minutes of discussion on visualizations.** The interviews with staff physicians were 1 hour in length with around 30 min allocated for discussion of the visualizations. Compared to other studies that collect user feedback from physicians, we had a lot of time with users and collected rich qualitative data. We also had a subject matter expert on our team which helped guide the designs and provide feedback through the design process.

- **Interview summary validation.** After the interviews were conducted, we validated the interviews by sending summaries back to the physicians which are significantly shorter than the full transcripts. The physicians were asked to provide feedback upon reading the summary and many replied acknowledging they had done so. There were a couple of times when changes to the summary were made after email communication with the physician. This process of validation was effective and likely had better outcomes than sending an entire transcript.

- **Two researchers conducted the study.** During the interviews, two interviewers were present (KS and EU) which allowed for debriefing discussions at the end of the interview. This also made the analysis process of the interviews a very collaborative process.

- **Engagement, diversity, and quality of participants.** The participants we interviewed were engaged and thoughtful in their responses. Many of the staff physicians are regarded as worldwide leaders in neuro-critical care and not only had experience in the clinical setting but also as researchers. The participants were recruited in Canada and the US however, many physicians were trained outside of North America, especially the trainees. As a result, the participants had varied exposure to interfaces and technology based on their backgrounds.

Despite these strengths, there are also several limitations we would like to highlight:

- **Time constraints in the interviews.** The interviews were 60 min in total and approximately half was allocated to the visualizations. However, there were times when the first 30 min of the interview took more time than anticipated, leaving less time for the visualizations. As a result, not all participants were shown every visualization.

- **Not all users of the bedside physiologic monitor were interviewed.** Nurses, neurosurgeons, and anesthesiologists all interact with the bedside physiologic monitor and may have differing opinions from the trainees and staff physicians we interviewed in critical care. We recommend future work to investigate the requirements and perceptions of different users.

- **The order in which the visualizations were presented had an impact on perception.** The physicians were always shown the ICP dose visualization first, followed by the individualized threshold, trajectory, and summation trend chart. This likely contributed to the understanding scores of the trainees and overall impressions of the visualizations. The physicians often compared the individualized threshold visualization to the dose visualization which indicates that were connecting their perceptions of a previous visualization to the visualization currently being shown.

7.2.2 Visualizations

The following are some strengths of the visualization design process and feedback received from the visualizations:

- **Multiple methods drove the design of the visualizations.** The visualizations were designed with inputs from the CWA (and AH), observations in the ICU, and discussions with our SME, Dr. Victoria McCredie. The visualizations were further refined with user feedback from trainees and staff physicians in critical care.

- **Hypothetical data was shown in the visualizations.** In the interviews, we showed hypothetical patient data that was reviewed by Dr. Victoria McCredie. This helped provide context for the visualization with hypothetical data for the patient.

- **Visualizations have applications beyond ICP.** The visualizations presented in the interviews were focused on ICP, however, they may have applications outside of ICP on a patient monitor. For example, the staff and trainee physicians noted that they would be interested in a dose visualization for CPP.

The following are some limitations of the visualization design process and feedback received from the visualizations:

- **Design requirements for initial visualizations were guided by one expert.** Despite the multiple methods employed to drive the design of the visualizations, the design requirements for the initial visualizations were guided by one expert in neuro-critical care. It would have been interesting to conduct interviews with staff physicians on information requirements before designing preliminary visualizations.

- **Visualizations were shown in isolation and out of the context of the ICU environment or real patient data.** The visualizations were viewed on the device screen of the interviewees (trainees and staff physicians). The visualizations were shown in isolation from one another and without the context of other patient information. This contributed to perceptions of some of the visualizations. For example, the physicians described that trajectory visualization did not give them very much information on the patient by itself. Although the physicians were told that the visualizations would be an addition to the bedside physiologic monitor and all other information would be available to them, this was not always appreciated by the comments. In addition, the data used for the visualizations was ‘clean data’ and did not have signal noise. The visualizations may have been perceived differently with real-life patient data.

- **The effectiveness of different visualization types was not tested.** In the preliminary usability assessment with trainees, we evaluated the understanding of the trainees on various visualizations. However, we did not test the effectiveness of different visualization types. For example, the ICP dose concept was shown in a summary visualization and a bar chart. However, there are different ways this could be visualized that can be explored that are presented in the following Section 7.4.

- **Accessibility of the visualizations and compliance with medical standards is a limitation of the visualizations.** As described in Chapter 6-Final Design, the dose visualization requires modifications of the colour palette or the addition of patterns to ensure they are distinguishable for individuals with various vision deficiencies. In addition, the design must be verified against standards such as IEC 60601: Product Safety Standards for Medical Devices to ensure markings (including fonts, trends, etc.) are clearly legible in varying light (IEC, 2020).

7.3 Impact of Covid-19

Covid-19 had an impact on this work. During the pandemic, ICU physicians were in high demand which made it challenging to recruit participants and ask for 60 min of their time. In addition, there were periods when our subject matter expert in neuro-critical care was very busy with clinical duties which proved difficult to receive feedback promptly. The study was conducted remotely which made it easier for physicians to connect on their personal devices at any time of day rather than having to meet in person. Additionally, we made our calendar available for interviews at all times of day 6 am-midnight, 7 days a week to accommodate the busy schedules of critical care physicians.

7.4 Outlook and Next Steps

The next step in neuro-critical care monitoring is the integration of data on one display. For any of the visualizations presented in this work to be possible, the variables that we are presenting must be available on one display with adequate storage to understand historic data. In addition to the data integration challenges, there will also be challenges with data accuracy and understanding which data is artefactual (i.e. when a transducer is moved from the patient's bedside or when a monitor is turned off to move a patient, etc.) or real (Hemphill et al., 2011). In addition, there are several future work recommendations that we have based on the findings of our work:

1) **Exploration of the effectiveness of different visualizations**

The visualizations we designed aimed to incorporate the results of the CWA and the neurophysiologic concepts. We designed one visualization for each concept (dose, trajectory, and individualized thresholds) and then an additional visualization to illustrate the relationship between three key variables in neuro-critical care (summation trend chart). The concept of ICP dose was one visualization that was challenging to represent. There are other ways that the concept of dose could be represented such as an ICP histogram (version 1 ICP dose visualization) or an ICP dose trend chart with each line representing the cumulative time spent in the ICP intensity range (see Figure 29 below).

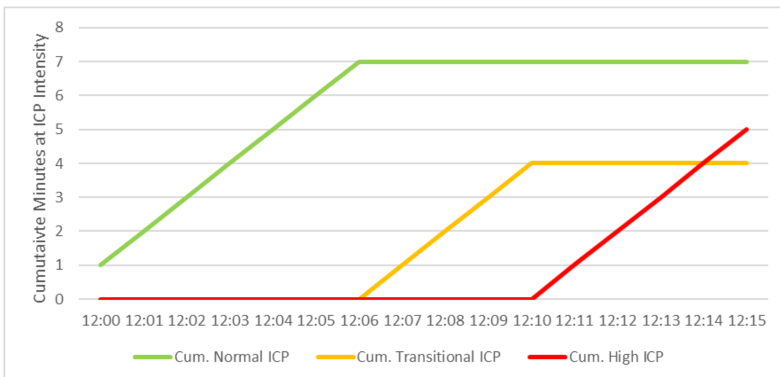


Figure 29: An alternative representation of the ICP dose

Each line corresponds to the cumulative minutes the patient has spent at that ICP intensity. If the line is horizontal, this indicates that the patient is not currently in that ICP intensity range. A positive slope indicates the patient is currently in that ICP intensity range and therefore the cumulative time in that range is increasing. This is one example of an alternative visualization that can be explored and evaluated against the current version to evaluate the effectiveness of different visualization types.

2) Exploration of the feedback of different users

As previously discussed in the limitations of the study design, a continuation of this research should investigate the perspectives of different users of the bedside physiologic monitor including nurses and neurosurgeons. As the staff physicians highlighted, the individual most likely to notice a change in the patient whether it be through the monitor or physical assessment will not be the physician, and therefore, the nursing perspective must be considered in future work.

3) **Exploration of different visualizations to incorporate other parameters and applications for non-continuous ICP monitoring.**

Although ICP is the most common brain-specific parameter monitored in the ICU, other physiologic variables were not explored in this research. Some variables that arose from conversations with physicians include brain tissue oxygenation, end-tidal CO2, Prx, ventilation, blood pressure, heart rate, clinical exam, and pupil diameter. Exploration of different visualizations that incorporate other parameters beyond ICP will be especially important to address the challenges associated with non-continuous ICP monitoring. As discussed, ICP is not always monitored continuously, therefore other visualizations must be explored. In addition to different variables, ICP waveform information was noted as an important diagnostic for patients. Future work should explore the extraction of the ICP waveform to make this information easier to analyze and make decisions with.

4) **Evaluate and address accessibility concerns and medical device standards.**

As discussed in Chapter 6, several challenges persist with the accessibility of the visualizations for individuals with red-green colour blindness. In addition to colour deficiency, the markings on the interface including the lines, legend, and annotations must be visible in varied light for all users. Standards such as ISO-60601-Prdocut Safety for Medical Devices as well as a comprehensive human factors assessment will need to be performed before implementing any visualizations on a bedside physiologic monitor.

5) **Collaboration with a monitoring company to integrate visualizations and evaluation in a longitudinal study.**

The outcomes of the usability study currently being conducted will help us understand if the bedside physiologic monitor + EID visualizations help trainees have greater SA and performance in clinical scenarios. If the results indicate that there is improvement in SA and performance, the next step will be a collaboration with a monitoring company to integrate the visualizations on a display and evaluate the impact of the display in a longitudinal study.

7.5 Conclusions

An EID approach combined with feedback from end-users was utilized to enhance the current bedside physiologic monitor. Visualizations were designed with the inputs of the CWA and observations as well as input from our subject matter expert, Dr. Victoria McCredie. Feedback from end users was collected through semi-structured interviews with trainees (preliminary usability assessment) and staff physicians (design refinement). The goal of this design process was to design an interface that can help support the expertise development of trainees in the neuro-ICU as well as improve situational awareness and decrease cognitive workload which will ultimately improve patient outcomes. Overall, the visualizations received positive feedback and any visualization usability elements were addressed in the designs to increase the usability of the prototype. Several recommendations for future work are identified based on the limitations of this study as well as feedback from the physicians on additional parameters and considerations for a display in the ICU. The prototype discussed in Chapter 6 is currently being tested in a usability study with trainee physicians.

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Appendix A
Letters

Recruitment Letter

Subject: Invitation to participate in an interview of exploring expertise development and interface design in critical care

Hello **______**,

Dr. Victoria McCredie, Dr. Catherine Burns, Kathleen Schaef, and I are working on an expertise development and interface design research project. I am a Systems Design Engineering PhD candidate at the University of Waterloo and am investigating critical care challenges that relate to the use of bedside physiologic monitoring in neuro-critical care and how critical care nurses, trainees and staff physicians develop expertise in the ability to detect, diagnose, and treat neurophysiologic deteriorations. We would like to conduct interviews with nurses, trainees and staff physicians to better understand how expertise development can be supported via interface design.

Interview Purpose

We are conducting interviews as part of a research study to explore the perceived challenges of trainees and staff physicians face in developing expertise development in neuro-critical care, and possible ways of how this can be improved through interface design.

The interview will take around 45-60 minutes via an online meeting. Please suggest a day and time over the next 2 months that's convenient for you. You can access this link [INSERT LINK] to schedule a suitable time.

We understand the timing for this interview is not ideal given the ongoing COVID-19 pandemic. However, the aim of our research is to develop advanced designs for interfaces that support decision-making, facilitate learning complex physiological relationships, and ultimately reduce the strain on our healthcare providers in the intensive care unit.

Remuneration

All trainees and staff physicians who participate in the interview will be given **150 CAD** in remuneration for time taken to participate.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB 42892). If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

Please contact me at euereten@uwaterloo.ca for questions or if you would like to take part in this research.

Thank you in advance for your time, participation and support.

Many thanks,

Ece Üreten, M.Sc., M.A.
PhD candidate
Advanced Interface Design Lab
University of Waterloo
eÜreten@uwaterloo.ca

Kathleen Schaef, B.Sc.
Master's student
Advanced Interface Design Lab
University of Waterloo
kschaef@uwaterloo.ca

Victoria McCredie, BSc, MBChB PhD FRCPC MRCPUK
Assistant Professor
Critical Care and Neuro-critical Care Medicine
Toronto Western Hospital
Division of University Health Network
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victoria.mccredie@uhn.ca

Catherine Burns, Professor
Canada Research Chair in Human Factors in Healthcare Systems
Executive Director, Health Initiatives and Sponsored Research
University of Waterloo
catherine.burns@uwaterloo.ca

Information Letter

University of Waterloo

[Insert Date]

Information letter for an interview study in critical care

This letter is an invitation to consider participating in a research study I am conducting as part of my PhD degree in the Department of Systems Design Engineering at the University of Waterloo under the supervision of Drs. Catherine Burns and Victoria McCredie. I would like to provide you with more information about this project and what your involvement would entail if you decided to take part.

Developing expertise is a complex process that takes years if not decades. Especially in dynamic and complex socio-technical systems, it is of utmost importance to perform highly. In critical care, expertise is required to provide the patient with correct and timely treatment. In case of lacking expertise, the effects of treatment can contain mistakes, incompleteness and even lead to life-threatening situations.

Conducting interviews will reveal in-depth insights of trainees and staff physicians. By understanding the mental models, challenges faced in critical care and ways how expertise is being developed over time, we want to contribute to a better design of physiologic bedside monitor interfaces, support the decision-making process and ultimately improve the quality of care and effectiveness of critical care.

Participation in this study is voluntary and a remuneration of 150 CAD will be provided even if participants choose to withdraw from the study. The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

We currently want to recruit participants (nurses, trainees and staff physicians) for an interview of 45 minutes, not more than 60 minutes in length to take place virtually.

In this interview, we want to hear about your experiences with the process of expertise development in critical care as well as your impression on some visualization concepts that we developed. These visualizations will be shown to you during the interview. Hearing your impressions will help us integrate some visualizations on a physiologic bedside monitor interface that will later be evaluated in a usability study.

You may decline to answer any of the interview questions if you wish so. You can request your data be removed from the study up until March 2022 as it is not possible to withdraw your data once papers and publications have been submitted to publishers. Further, you may decide to withdraw from this study at any time without any negative consequences by advising the researcher. With your permission, the interview will be audio and video recorded to facilitate collection of information, and later transcribed for analysis.

Shortly after the interview has been completed, I will send you a copy of the transcript to give you an opportunity to add or clarify any points that you wish. If you wish to add or change anything mentioned in the transcript, please contact me at eÜreten@uwaterloo.ca before March, 2022.

Your identity will be confidential. Any identifying information will be removed from transcripts and stored separately, and the video recordings will be deleted after the transcripts are finalized and stored. Your name will not appear in any thesis or report resulting from this study, however, with your permission anonymous quotations may be used. Data collected during this study will be securely stored for at least 7 years on a password-protected One Drive account and secure computers.

The interview will be conducted over an online platform, Microsoft Teams. Microsoft Teams has implemented technical, administrative, and physical safeguards to protect the information provided via the Services from loss, misuse, and unauthorized access, disclosure, alteration, or destruction. However, no Internet transmission is ever fully secure or error free.

The findings of this interview study will help us to come up with design ideas for a physiologic bedside interface used in neuro-critical care units. A second study is planned to investigate how interface design can support expertise development.

There are no known or anticipated risks to you as a participant in this study.

This study has been reviewed and received ethics clearance through the University of Waterloo Research Ethics Board (REB 42892). If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

For all other questions or if you would like additional information to assist you in reaching a decision about participation, please contact me by email at eÜreten@uwaterloo.ca. You can also contact my supervisor, Professor Catherine Burns at 519-888-4567 ext. 33903 or email catherine.burns@uwaterloo.ca.

I hope that the results of my study will be of benefit to those organizations directly involved in the study, other voluntary recreation organizations not directly involved in the study, as well as to the broader research community.

I very much look forward to speaking with you and thank you in advance for your assistance in this project.

Yours Sincerely,

Ece Üreten, M.Sc., M.A.
PhD candidate
Advanced Interface Design Lab
University of Waterloo
euereten@uwaterloo.ca

Kathleen Schaef, B.Sc.
Master's student
Advanced Interface Design Lab
University of Waterloo
kschaef@uwaterloo.ca

Victoria McCredie, BSc, MBChB PhD FRCPC MRCPUK
Assistant Professor
Critical Care and Neuro-critical Care Medicine
Toronto Western Hospital
Division of University Health Network
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Catherine Burns, Professor
Canada Research Chair in Human Factors in Healthcare Systems
Executive Director, Health Initiatives and Sponsored Research
University of Waterloo
catherine.burns@uwaterloo.ca

Feedback Letter

Project Title: Exploring expertise development, interface design and evaluation in neuro-critical care

Student Investigator: Ece Üreten, SYDE, euereten@uwaterloo.ca, Kathleen Schaef, SYDE, kschaef@uwaterloo.ca

Faculty Advisor and Principal Investigator: Catherine Burns, SYDE,

catherine.burns@uwaterloo.ca

We appreciate your participation in our study and thank you for spending the time helping us with our research!

In this study you shared your experiences as a critical care physician with regards to expertise development and mental strategies for certain critical care scenarios. The purpose of this study is to investigate the challenges faced in developing expertise within critical care, understand ways of how you have been developing expertise over time and hear about strategies that you would apply if confronted with a specific neuro-critical care scenario.

Your identity will be confidential. Your name will not be included or in any other way associated, with the data collected in the study. Data collected during this study will be securely stored for at least 7 years on a password-protected One Drive account and secure computers. All identifying information will be removed from the records prior to storage.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB ***42892)***. If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

For all questions feel free to contact me at euereten@uwaterloo.ca or my research team.

We really appreciate your participation, and hope that this has been an interesting experience for you.

Ece Üreten, M.Sc., M.A.
PhD candidate
Advanced Interface Design Lab
University of Waterloo
euereten@uwaterloo.ca

Kathleen Schaef, B.Sc.
Master's student
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kschaef@uwaterloo.ca

Victoria McCredie, BSc, MBChB PhD FRCPC MRCPUK
Assistant Professor
Critical Care and Neuro-critical Care Medicine
Toronto Western Hospital
Division of University Health Network
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Catherine Burns, Professor
Canada Research Chair in Human Factors in Healthcare Systems
Executive Director, Health Initiatives and Sponsored Research
University of Waterloo
catherine.burns@uwaterloo.ca

Appendix B
Study Protocol

Consent Script

Introduction:

Hello. I'm Ece Üreten. I am conducting research about exploring expertise development, interface design and evaluation in neuro-critical care. This interview is part of my PhD studies at the University of Waterloo, in the Systems Design Engineering department in Waterloo, Ontario. I'm working under the supervision of Professor Catherine Burns of UWaterloo's department of Systems Design Engineering.

Thank you for your interest in participating in my research.

Have you had time to read the Letter of Information I sent you?

YES:

Great, then I would like to take a moment to review some main points from the Letter of Information before we continue.

NO:
(Proceed with LOI summary)

Confirm the following to the participant:

- Your participation in this study is voluntary.
- If you do not want to answer some of the questions you do not have to, but you can still be in the study.
- You can decide to stop at any time, even part-way through the interview for whatever reason.

- If you decide to stop during the interview, we will ask you how you would like us to handle the data collected up to that point, whether returning it to you, destroying it or using the data collected up to that point.
- You can ask to remove your data from the study up until approximately **March 2022.**
- Collected data will be de-identified and stored securely on a password-protected OneDrive account/secure computers.
- This study has been reviewed and cleared by the University of Waterloo Research Ethics Board.

Do you have any questions or want me to go over any study details again?

Consent questions:

Do you agree to participate in this study?

If yes,

- Do you agree to your interview being audio recorded to ensure accurate transcription and analysis."
- Do you agree to your study session being video recorded with the understanding that the video recordings will be deleted after the transcripts are finalized?
- Do you agree to the use of anonymous quotations in any thesis or publication that comes from this research?
- (Trainees only) Do you agree to be contacted for a a second research study as described in the information letter (YES/NO)? How do you prefer to be contacted? (e.g. by email)
- Would you like a copy of the study results? If yes, where should we send them (email, mailing address)?
- Do you allow de-identified study data to be stored and used for future research? (YES/NO)

If no, "Thank you for your time."

Trainee Questions

Demographics

Before we start, I would like to ask some questions regarding demographic information.

1. **Are you currently a trainee in critical care medicine?**

a) Yes o
b) No o

---

2. **Which year of residency are you in?**

---

3. **What specialty certifications do you hold?**

o Anesthesiology
o Emergency Medicine
o Critical Care
o General surgery
o Internal medicine
o Neurosurgery
o Neurology
o Respirology

o None
o Other, please specify ______________________

4. **Which gender do you identify with, do you prefer not to say?**

---

5. **What is your age?**

o < 30 years
o 30 - 39 years
o 40- 49 years
o 50 - 59 years

Thank you for the information.

Overall, we will talk about four parts; firstly, your understanding of expertise in critical care, secondly, challenges faced in expertise development, thirdly, one specific critical care topic, and finally ways to improve the expertise development process.

Through your participation, you will contribute to the research we are conducting to better understand physicians' perspectives and the future development of supporting physicians with decision-making including the bedside monitor interface in neuro-critical care.

Main part of the study

This is the first part of the interview, where we will be asking you questions to get to know you better. Remember you don't have to answer if you don't want to, and we can always come back to questions you want to think a bit more about.

Part 1: Expertise in critical care

Participant	Question	Operationalization (Blessing & Chakrabarti, 2009)
Novice (trainee)	Can you share with us, what ~~is~~ tasks are involved in your current role? (e.g. preparation of patient for staff physicians' assessment, how do you do that? What are your everyday goals and tasks) What area of expertise in critical care are you looking to develop (more) during your training? (e.g. are you specifically interested in a topic within neuro-critical care? If yes, which?)	Getting to know the participant. Identification of area of expertise
Novice	When you consider people who are classed as an expert in your field (of critical care), what characteristics are you considering? (e.g. they react out of intuition, they are fast, they have multiple strategies in their minds) Probes: When will you know that you are an expert? Or what do you think you need to do to achieve this? (e.g. familiarity with various cases? Out of the box thinking?)	General understanding of an expert and novice

Novice	When you think of people who are developing their expertise but not an expert yet, what comes to your mind as the difference between them and someone you would consider an expert? (e.g. people are insecure about their actions? They make more mistakes?) If you consider your training in critical care, what are the main skills you think you are developing over time, that will make you an expert in this area? (e.g. practical and theoretical knowledge)	General definition of an expert and novice Understand main skills they developed to become an expert

Thank you for your explanations.

Through a search of the literature we looked at how expertise can be developed we are especially interested in how this is portrayed in the critical care area. More specifically, we identified some major areas such as not only physical skills but also mental strategies or models that develop over time, and experts act intuitively and automatically, without thinking too long about their steps because they have done it already so many times and in various ways.

So, our next questions focus especially on intangible ways to develop expertise, and we are interested in your perspective and experience about that.

Part 2: Expertise development strategies

Participant	Question	Operationalization
Novice	Imagine you have the staff physician standing next to you, can you tell us how they are usually trying to convey their strategies to the trainees? E.g., How do they show their mental models or thinking process to approach the patient case?	Understand how seniors convey their mental models to fellows
Novice	How do you shape your **own** mental models in critical care? (e.g. you feel you know the right strategies to apply for a patient and immediately know what to do)	Understand how they support individual mental model development in critical care
Novice	How can you tell you are progressing? What are some of the indicators you check?	Identification of successful strategies to develop expertise

	(e.g. do you often get feedback on your actions? Do your mentors acknowledge how much you contributed to the betterment of the patient's health?)	
Novice	From your experience, can you share with us what you think you in general struggle with the most when they develop expertise? (e.g. mentors don't tell you what to do but you need to figure it out yourself, "learning by doing" or trial and error) Have you heard any other struggles from other trainees? (e.g. there is little explanation on how to use the technology in the ICU and how to understand the data presented. OR they'd want more feedback to see if their actions were correct)	Identification of challenges to develop expertise

These were general strategies and you talked about a specific case. I would like to better understand how the bedside physiologic monitors in ICU impacts expertise development.

Participant	Question	Operationalization
Novice	Can you tell me which bedside physiologic monitors you have experience with? Do you use one more commonly than the others? Philips/GE - cardiac - respiratory - neurological: ICP, EEG, quantitative pupillometry, brain tissue oxygen, brain temp, cerebral autoregulation, cerebral blood flow, brain ultrasound (incl transcranial Doppler), Can you think back to an example with a recent patient, how did you identify the past and current of the patient's health by using the bedside physiologic monitor?	Identification of currently used bedside/station monitor Identification of approach to proceed with patients' past, current and future states, when using the bedside monitor
Novice	What do you like most about the bedside monitoring systems you have worked with so far? (e.g. it's very intuitive to use)	Identification of aspects the participant likes most and least and finds easy or difficult. Understand possible support

	Probes: Why is it easy or difficult?	provided through bedside monitor for expertise development

Now I would like to focus on specific cases (you mentioned before).

Part 3: Specific topic in critical care

Participant	Question	Operationalization
Senior	If you reflect about the neuro-critical care cases you came across so far, have you ever felt that some concepts are especially difficult to explain, and if so, can you share why? You can share some examples if you like. (Are there any neuro-critical care cases that you think are difficult for trainees to understand? If so, why? Can you share some examples?) How would you say that the Intracranial Pressure concept could be a rather difficult concept to explain and deal with? Or is it rather straight-forward to monitor, assess and predict patients' states? Can you share with us, what are the key concepts that you recall about ICP monitoring? How did you learn about ICP monitoring, e.g. ICP numeric ranges, waveform interpretations? If you have a patient who has (high) abnormal ICP, what do you pay attention to when using the monitoring system especially? How often do you check the patient's status? What would you consider as a critical situation on this patient? / What would a critical ICP case look like to you? Why?	Finding challenging case examples for critical care

	Which other variables come to your mind to cross check ICP values or waveform pattern changes?	

We would like to show you some static sketches of ICP visualizations now.

Imagine you can see this visualization on a bedside physiologic monitor and you have a patient that is connected to an ICP monitor. Please keep in mind that these visualizations would be an additional and not shown in isolation on a bedside physiologic monitor.

ICP dose

Can you tell me how you understand the visualization and what it is telling you? Please describe it in as much detail as possible.

Probes:

- Bar chart
    - Can you comment on what is happening to the patients ICP
    - Can you tell me how you interpret the % on the bars
    - Can you tell me how you interpret the numbers in the white boxes along the grey line
    - Can you tell me how you interpret the grey line
    - Can you tell me how you interpret the colour coding
- Donut chart
    - Can you tell me how you interpret the number in the middle of the visualization

What conclusions do you draw about this patient based on the visualization?

What timescale is most valuable for you when evaluating a patient?

How are ICP targets tracked in the center you work in?

If you were to rank this visualization from 1 to 5 on how intuitive and easy to understand, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified to increase this ranking?

If you were to rank this visualization from 1 to 5 on how useful the information is for your assessment and understanding of the patient's condition, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified or added to increase this ranking?

Individualized Threshold

Can you tell me how you understand the visualization and what it is telling you? Please describe it in as much detail as possible

Probes:

- Can you comment on the colour coding?
- Can you tell me how you interpret the values above the black line?

What conclusions do you draw about the patient based on these visualizations?

If you were to rank this visualization from 1 to 5 on how intuitive and easy to understand, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified to increase this ranking?

If you were to rank this visualization from 1 to 5 on how useful the information is for your assessment and understanding of the patient's condition, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified or added to increase this ranking?

Trajectory

Can you tell me how you understand the visualization and what it is telling you? Please describe it in as much detail as possible.

Probes:

- Can you comment on the colour coding of the top visualization?
- Can you tell me how you interpret the two visualizations (and % numbers) on the bottom row?

What conclusions do you draw about the patient based on this visualization?

If you were to rank this visualization from 1 to 5 on how intuitive and easy to understand, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified to increase this ranking?

If you were to rank this visualization from 1 to 5 on how useful the information is for your assessment and understanding of the patient's condition, how would you rank it? (1-poor 5-excellent)
-Follow up: What elements could be modified or added to increase this ranking?

Summation trend chart

Can you tell me how you understand the visualization and what it is telling you? Please describe it in as much detail as possible.

Probes:

- What is the ICP, MAP and CPP value at 12:08

What conclusions do you draw about the patient based on this visualization?

If you were to rank this visualization from 1 to 5 on how intuitive and easy to understand, how would you rank it? (1-poor 5-excellent)
Follow up: What elements could be modified to increase this ranking?

If you were to rank this visualization from 1 to 5 on how useful the information is for your assessment and understanding of the patient's condition, how would you rank it? (1-poor 5-excellent)
Follow up: What elements could be modified or added to increase this ranking?

Final Questions

If we were to design an interface making sure we have all the variables needed, what other readings would you require to treat a patient.

-Probe: In addition to the variables, we have discussed including average ICP, MAP and CPP, are there any other physiologic variables on a monitor that would be helpful in making your assessment?

If you could choose 1 or multiple of these visualizations to put on a bedside monitor interface, which ones do you believe would be most useful to assess the current patients state, predict future states and understand trends?

Staff physician questions

1. Are you currently a staff physician in a critical care unit within Canada or the U.S.?

c) Yes ☐ in Canada ☐ in the U.S. ☐
d) No ☐

---

2. How many years have you been in independent practice?

---

3. What specialty and subspecialty certifications do you hold?

☐ Anesthesiology
☐ Critical Care
☐ Internal medicine
o Neurology
☐ Emergency Medicine
☐ General surgery
☐ Neurosurgery
o Neuro-critical care

☐ Respirology
☐ None

☐ Other, please specify ____________________

4. Which gender do you identify with, do you prefer not to say?

---

5. What is your age?

☐ 30 - 39 years
☐ 40- 49 years
☐ 50 - 59 years
☐ > 59 years

---

6. What types of patients are cared for in your ICU?

☐ Medical
☐ Surgical
☐ Neurotrauma/Neurosurgical
☐ Trauma
☐ Cardiovascular surgical
☐ Coronary
☐ Burns
☐ Other, please specify: ___________________

7. **Do you work in a university or community hospital?**

☐ University hospital

☐ Community hospital

8. **Do you have residents or fellows training in your ICU?**

☐ Yes

☐ No

Thank you for the information.

e) Overall, we will talk about 4 parts; firstly, your understanding of expertise in critical care, secondly, challenges faced in expertise development, thirdly, one specific critical care topic, and finally ways to improve the expertise development process.

Through your participation, you will contribute to the research we are conducting to better understand physicians' perspectives and the future development of supporting physicians with decision-making including the bedside monitor interface in neuro-critical care.

Main part of the study

This is the first part of the interview, where we will be asking you questions to get to know you better. Remember you don't have to answer if you don't want to, and we can always come back to questions you want to think a bit more about.

Part 1: Expertise in critical care

Participant	Question	Operationalization (Blessing & Chakrabarti, 2009)
Senior	Can you share with us, what ~~is~~ tasks are involved in your current role? (e.g. are you regularly mentoring residents or fellows in your unit?)	Getting to know the participant. Identification of area of expertise

	If you were to describe your area of expertise within critical care, what would it be? (e.g. research/education/quality improvement or clinical focus- neuro/resp/cardiac etc	
Senior	When you consider people who are classed experts in critical care medicine, what characteristics are you considering? Probes: When did you know that you were an expert?	General understanding of an expert and novice
Senior	When you think of people who are developing their expertise but not an expert yet, what comes to your mind as the difference between them and an expert like yourself? If you were to think back to your training in critical care, what were the main skills you think you developed over time, that made you an expert in this area?	General definition of an expert and novice Understand main skills they developed to become an expert

Thank you for your explanations.

Through a search of the literature we looked at how this is portrayed in the critical care area. More specifically, we identified some major areas such as not only physical skills but also mental strategies or models that develop over time, and experts act intuitively and automatically, without thinking too long about their steps because they have done it already so many times and in various ways.

So, our next questions focus especially on intangible ways to develop expertise, and we are interested in your perspective and experience about that.

Part 2: Expertise development strategies

Participant	Question	Operationalization
Senior	Imagine you have a trainee standing next to you, can you tell us how you are trying to convey your strategies(mental models) to the trainees? E.g., How do you show certain strategies to approach the patient case?	Understand how seniors convey their mental models to fellows

Senior	How do you support trainees to develop **their own** mental models in critical care?	Understand how they support individual mental model development in critical care
Senior	How can you tell your trainees are progressing? What are some of the indicators you look for?	Identification of successful strategies to develop expertise
Senior	From your experience, can you share with us what you think trainees struggle with the most when they develop expertise?	Identification of challenges to develop expertise

These were general strategies and you talked about a specific case. I would like to better understand how the bedside physiologic monitors impact expertise development.

Participant	Question	Operationalization
Senior	Which bedside physiologic monitor do you currently use in your ICU? Can you tell me which bedside physiologic monitors you have experience with? Do you use one more commonly than the others? Philips/GE - cardiac - respiratory - neurological: ICP, EEG, quantitative pupillometry, brain tissue oxygen, brain temp, cerebral autoregulation, cerebral blood flow, brain ultrasound (incl transcranial Doppler), Can you think back to an example with a recent patient,, how did you identify the past and current of the patient's health by using the bedside physiologic monitor? And did you use this data to predict the future state? If so, how?	Identification of currently used bedside/station monitor Identification of approach to proceed with patients' past, current and future states, when using the bedside monitor
	What do you like most about the current bedside monitoring system in your ICU? What do you like least? Can you elaborate on these concerns? Probes: Why is it easy or difficult?	Identification of aspects the participant likes most and least and finds easy or difficult. Understand possible support provided through bedside

		monitor for expertise development

Now I would like to focus on specific cases (you mentioned before).

Part 3: Specific topic in critical care

Participant	Question	Operationalization
Senior	If you reflect about the neuro-critical care cases you came across so far, have you ever felt that some concepts are especially difficult to explain, and if so, can you share why? You can share some examples if you like. (Are there any neuro-critical care cases that you think are difficult for trainees to understand? If so, why? Can you share some examples?) How would you say that the Intracranial Pressure concept could be a rather difficult concept to explain and deal with? Or is it rather straight-forward to monitor, assess and predict patients' states? Can you share with us, what are the key concepts that you recall about ICP monitoring? How did you learn about ICP monitoring, e.g. ICP numeric ranges, waveform interpretations? If you have a patient who has (high) abnormal ICP, what do you pay attention to when using the monitoring system especially? How often do you check the patient's status? What would you consider as a critical situation on this patient? / What would a critical ICP case look like to you? Why?	Finding challenging case examples for critical care

	Which other variables come to your mind to cross check ICP values or waveform pattern changes?	

Neuro-physiologic Concepts

- Staff physicians were presented three key neurophysiologic concepts.
    - Secondary insult dose
    - Individualized thresholds
    - Trajectory
- Staff physicians were asked if there was anything that was missing from the concepts presented

Visualizations

We would like to show you some static sketches of ICP visualizations now. These visualizations are designed to be displayed as an addition to the standard bedside physiologic monitor. For each visualization, we will first explain the goal of the visualization and we would love to hear your feedback on how you believe it could be used on a bedside physiologic monitor.

ICP Dose

For each visualization, a general discussion took place. Some probes include:

- Do you believe there is value in having both styles of dose visualization?
- Is there anything you find confusing in the visualization?
- What is the most appropriate title for the left y axis on the bar chart
- Is average ICP a common way to communicate ICP in the ICU?
- What time frame are you most interested in when evaluating a patient?

General discussion of concerns trainees had with the visualization.

Individualized Thresholds

For each visualization, a general discussion took place. Some probes include:

- In your current workflow, how do you understand a patient's trend and historic values?

- How do you track ICP targets for patients?
- What time frame do you tend to look at for patients with ICP monitoring?

General discussion of concerns trainees had with the visualization.

Trajectory

For each visualization, a general discussion took place. Some probes include:

- How is a patient's ICP typically communicated?
- What time frame are you most interested in for evaluating a patient's change in ICP?

General discussion of concerns trainees had with the visualization.

Summation Trend Chart

For each visualization, a general discussion took place. Some probes include:

- What relationship of variables is most important in the neuro-ICU?
- Is autoregulation evident in this visualization?
- Do you have a preference for the different visual representations of the visualization?

General discussion of concerns trainees had with the visualization.

Final Questions

- What visualization or combination of visualizations do you believe would provide the most value on a bedside physiologic monitor. Please feel free to say zero or multiple.
- Based on what we showed you today, is there anything we are missing that would help support decision making, and expertise development in neuro-critical care?

Appendix C
Interface Training

Hello and thank you so much for your interest in participating in our study on interface design in neurocritical care. In this training video, we will walk you through the different parts of the interface that will be tested and evaluated in this study.

Vitals Tab

The first screen you will see is the vitals screen. This screen is similar to commonly used bedside physiologic monitoring in the ICU currently. On the top header, you can see that there are two other tabs that I will explain further later in this video. On the header, you can find the patient's name and sex, Rebecca Wong, Female. In addition, the current date and time is also displayed in the top right-hand corner. Note that this date and time may be different than the current date and time as we are simulating a scenario.

The “i” icon on the top left-hand corner has information about the scenario that will be evaluated, and the patient’s flowsheet filled in by the nurses. For this patient, the flowsheet is currently left blank. In the scenarios presented to you later, you might find different documentation times which might be different to the common starting time at 9:00 am.

The main section of the screen includes the patient’s real time vitals including HR, ABP, ICP, SPO2, Respiratory rate, Cerebral perfusion pressure and end tidal CO2. Each vital sign has an upper and lower limit shown by the top and the bottom number to the left of the real time vital sign.

Looking at the bottom of the vitals screen, the only clickable interactive element is patient info for this study. The patient info pop-out gives basic information on the patient such as the patient ID, name, sex and age.

On the right-hand side of the screen, there is an ICP summary for the patient. Below this summary at the bottom of the screen is where you can select the time frame of interest and the two options are the past hour and past 6 hours for that patient. This ICP summary recalculates every 30min. At the top of the ICP summary, you will find the ICP time burden bar. This bar represents the percentage of time that the patient has spent in various ICP ranges which we refer to as “burden”.

The green range represents normal ICP and ranges from 0-15mmHg (millimeter mercury). The yellow range represents transitional ICP and ICP values between 15-20mmHg. The light red range represents high ICP and ICP values between 20-30mmHg and the dark red represents very high ICP and values of ICP greater than 30mmHg.

The percentages on the bar graph indicate the percentage of time spent in each ICP range for that selected period. For this patient on the 1-hour summary, they spent 25% of the past hour in a normal ICP, 25% in a transitional ICP range, 40% in a high ICP ranges, and 10% in a very high ICP range. At the bottom of the ICP summary, the trend for ICP over the selected time frame is shown as well as the percent change of ICP. A positive number indicates an increase in ICP over the selected time frame. Below the ICP trend, the average, minimum and maximum ICP are shown for the selected time frame.

One last element on this screen is a notification icon on the top right-hand corner to the left of the date and time. A notification for autoregulation reading “impaired autoregulation?” will appear if the % change in 1 hour is greater than 30% (and the ICP value is more than 15 mmHg) or if ICP is greater than 20 mmHg. This does not mean the patient is not autoregulating, however, it may be something to consider based on how ICP is changing.

ICP Burden

The second tab is the ICP burden that can be accessed by the top header. This screen contains information on the patients’ ICP trend over the selected period and how much time the patient has spent in each ICP range. Looking at the bar graph, the left y axis represents ICP Time Burden as a percentage, the right y axis represents the average ICP, and the x axis represents time. The white line represents the average ICP and is read on the right y axis, whereas the bars are read on the left y axis.

Looking at each of the bars, in this view, the bars represent a 1-hour period with each color on the bar showing the amount of time that the patient spent in a particular ICP range. For example, from 2:00 to 3:00, this patient spent 88% of their time at a high ICP range, 12% of their time at a transitional ICP range and their average ICP over the hour was 22mmhg. From 3:00 to 4:00, this patient spent 68% of their time at a transitional ICP range, 32% of their time at a normal ICP range and their average ICP over the hour was 16mmHg. If you hover over the bar, the max ICP value for the hour will appear as well as the percentages for each range including the average.

If you forget the ICP ranges, the ICP ranges are described by the top right box adjacent to the graph which shows the high and low value for each respective range. These ranges are also shown on the top of the bar graph in the legend and by clicking on the box, you are able to hide them from the graph. This is also a feature for the average line if you click on the white circle.

To adjust the time scale of the graph there are two options. The first is to use the slider at the bottom of the graph. This slider shows the bars for high ICP. You are able to increase the number of bars shown or navigate through the timeline for that day. The second way to adjust the time scale of the bar graph is to use the duration selector to the right of the date. The date selector is not interactive on the interface as we will only be showing 1 day of data.

The last section of this screen is the annotations. For the time-period selected, annotations for medication, patient position etc. will appear and can be filtered by annotation type using the filter icon to the right of type. The time stamps of the annotations can also be found at the bottom of the bar graph as blue points along the x axis and the timeline adjuster. For this view, you can see there were annotations between 2:00-3:00 and 4:00-5:00 which corresponds to the annotations panel on the right-hand side.

Pressures

The third screen is the pressures screen and can be accessed by the top header. Another way to access this screen is by clicking the hour of interest on the ICP burden screen and then the detailed view will open on the pressures tab. For example, on this patient you may be interested in looking at 3:00-4:00 in more detail because there is an annotation indicated by the blue dot and in addition, the ICP was high for this hour. (You can click on the hour in the x axis to bring you to this time frame on the pressures tab.)

The top graph is a summation graph for CPP and ICP which sum to MAP based on the key hemodynamic equation that CPP is the difference between MAP and ICP.

In this graph, CPP represented by the purple area and ICP represented by the light grey area are stacked on top of one another to give the sum which represents MAP represented by the red line. For example, at 00:20 the patients' CPP is 60mmHg, and their ICP can be read by the height of the white area which is about 30mmHg at 00:20. The patients MAP is the sum of both of these variables (ICP and CPP) represented by the red line and is approximately 90mmHg at 00:20.

The exact values are available when you hover over the time of interest. On the top graph, the variables can be viewed one at a time by deselecting the variables by clicking on the legend for CPP, MAP and ICP.

The bottom graph shows the patients ICP as a grey area and threshold targets for transitional, high and very high ICP represented by dashed lines.

These threshold targets are the same as those represented on the ICP burden screen. These targets may be adjusted by a senior critical care clinician or by orders from neurosurgery. On the current interface, you will not be able to adjust these.

For example, if a patient's ICP was stable at 18mmHg, the visualizations may be adjusted so that 18mmHg represents a normal ICP for that patient rather than transitional. When targets are not customized the default targets for each range are less than 15mmHg for normal, 15-20mmHg for transitional, 20-30mmHg for high, and greater than 30mmHg for very high.

For this patient, from 2:00-2:30, the patient's ICP was in high and it dropped down to a transitional range and then normal range starting at about 4:00. If the ICP grey area is below the yellow dashed line, this indicates that the patient is in a normal ICP range. If the ICP grey area is above the yellow dashed line and below the light red line (or second dashed line) this indicates that the patient is in a transitional ICP range. If the ICP grey area is above the light red line and below the dark red line, this indicates that the patient is in the high ICP range. Lastly, If the ICP grey area is above the dark red dashed line, this indicates the patients ICP is in the very high ICP range.

The time scale can be adjusted the same way as the ICP burden tab and the annotations are also viewed on the graph.

Conclusion

At this point, you have completed the training video for the interface. The interviewers will be happy to answer any clarifying questions you may have about any of the graphics or sections of the interface prior to beginning the scenarios. Thank you.